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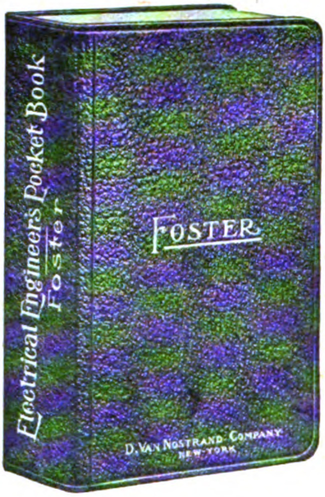

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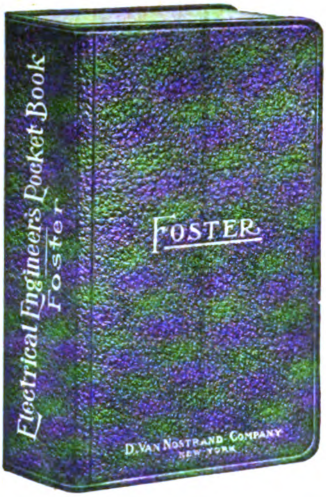

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AN EXHAUST STEAM TURBINE PLANT

BY HENRY H. WAIT

At the Wisconsin Steel Company's Mill at South Chicago the turbine utilizes the exhaust steam from a reversible engine which drives the blooming rolls. The steam passes first to the receiver which takes out the shock of the puffs of steam, thence to the steam accumulator or " regenerator ", and from there to the turbine and condenser. The general layout of the plant is shown in Fig. 2.

As this is the first plant of this character to be installed in this country, it was subjected to an elaborate series of tests by Mr. A. U. Leonhauser, the chief engineer of the Wisconsin Steel Company, and Mr. F. G. Gasche, mechanical engineer of the Illinois Steel Company. Besides testing the turbine equipment, the arrangement offered an opportunity to test the steam consumption of the primary engine by making a temporary change in the piping, so that the exhaust was led directly to the condenser without passing through the turbine. Mr. Gasche has already published an account of the various tests, giving very interesting continuous indicator diagrams of the engine and charts of the roll-train resistance etc.*

Primary engine. This is a 42 by 60 double-cylinder engine, of the rolling-mill type. When in normal operation the engine rolls about 19 ingots per hour with 21 passes per ingot, stopping and reversing after each pass with a short interval for the starting of a new ingot, so that it is stopped or practically idle 20% of the time during the cycle required for turning out an ingot. There are other frequent stops for the ordinary manipulation of the mill which last from a few seconds to several minutes.

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*" Power " June 1907.

233408

The average i.h.p. while the engine is actually running is 1010, and if the total work per hour were distributed evenly over the hour, the average i.h.p. for the hour would be 820. Figuring back from the total steam consumption, gives 64 pounds of steam per average i.h.p. for the hour, or 54 pounds during the running period. This large consumption is readily understood when we consider that the engine takes steam for practically the full stroke when starting the passes, and is running on very light load most of the rest of the time. Of course the horse power, and especially the torque, runs up enormously when the rolls first take hold of the ingot.

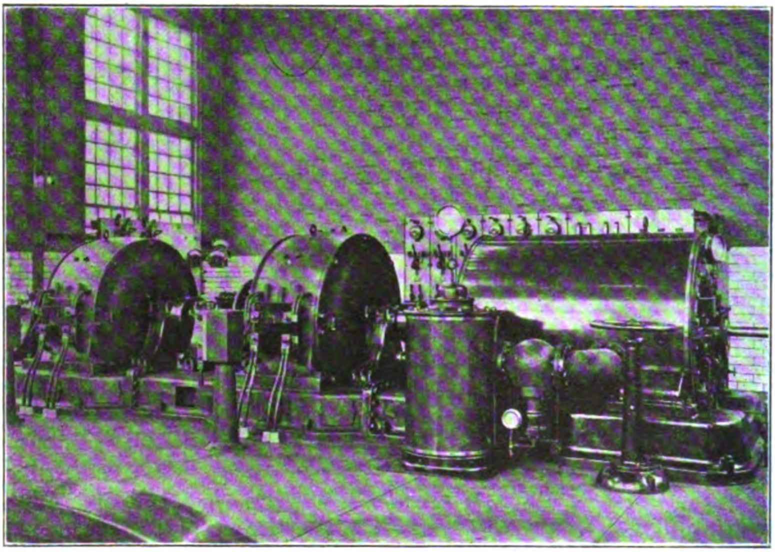

FIG. 1

Receiver. This is the vertical drum shown on the left of Fig. 3. When the engine is exhausting directly to the atmosphere and is taking steam at nearly full stroke, the puffs of steam shoot a long distance up in the air and make a noise like a number of big locomotives puffing in unison. The receiver is to relieve the accumulator of the strains and disturbance which would occur if the puffs went directly to it. The receiver consists of a tank with a number of baffle-plates and is provided with drains for water and oil. At the top of the receiver, between it and the vertical exhaust-pipe, used when desired to exhaust directly to

atmosphere, will be seen the relief valve which permits the escape of steam to the air during the periods when there is more than the demands on the turbine and regenerator require.

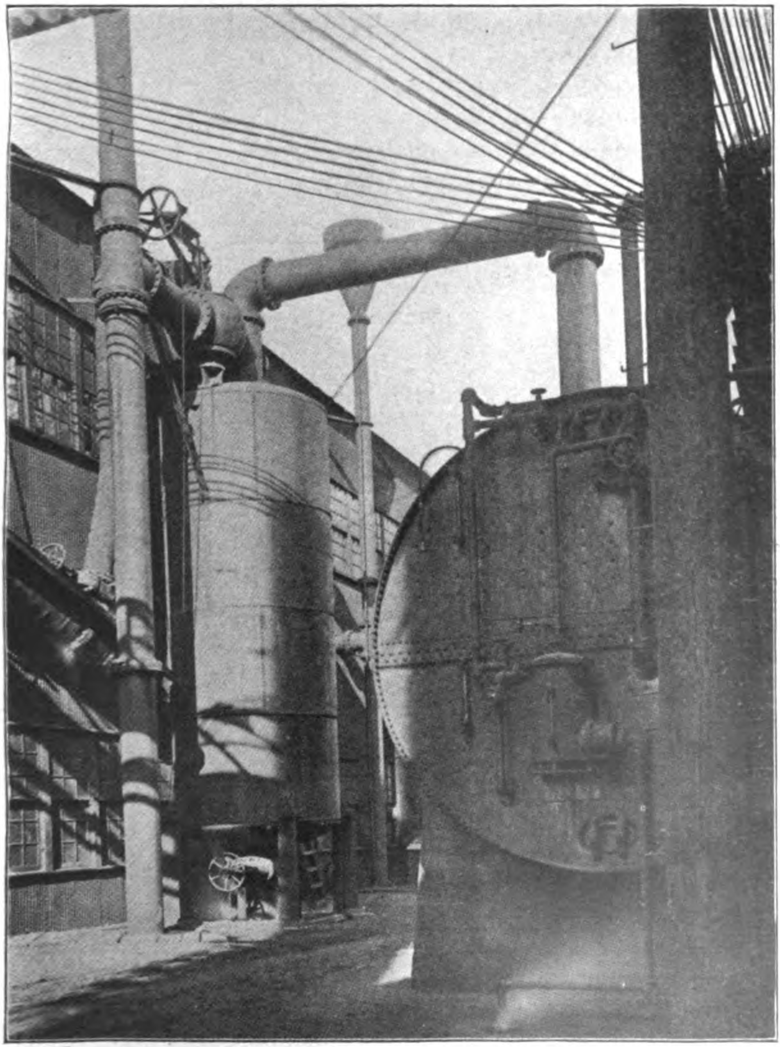

FIG. 3

Accumulator. The accumulator or regenerator is a very interesting piece of apparatus and is virtually the same as the more recent Rateau regenerators built in Europe. It is shown in Fig. 4. Longitudinal and transverse cross-sections of a small regenerator are shown at the right in Fig. 2.

Principle of operation. The accumulator might be called a heat fly-wheel, absorbing or giving up energy in accordance with the requirements. It might also be likened to a storage-battery floating on the line.

When the engine is running, the exhaust steam comes from the engine through the receiver and is delivered to a number of pipes immersed in the water in the regenerator. These pipes or ducts are perforated with a number of small holes, spraying the steam, so to speak, in through the mass of the water in the regenerator. A greater or less proportion of this steam is condensed in passing through the water and gives up heat to the mass of water in the regenerator.

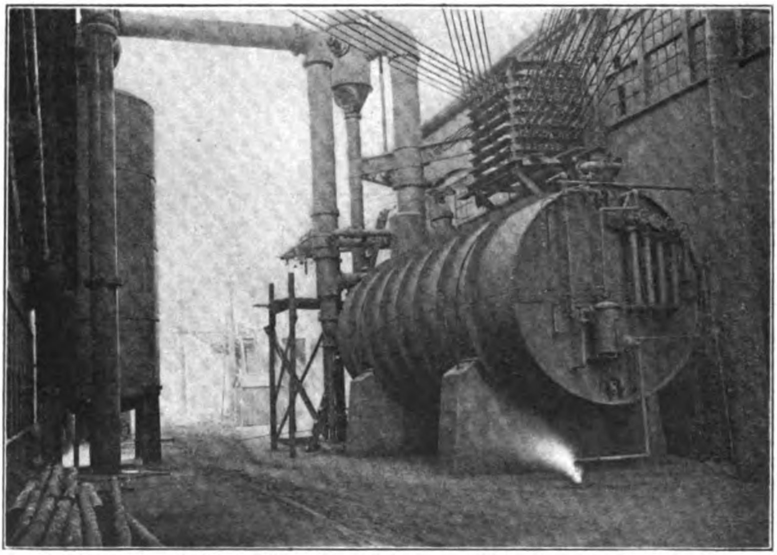

Fig. 4

It is usual to operate the regenerators at about atmospheric pressure. In other words, the steam coming to the regenerator will usually have a temperature of 212° fahr. and will tend to heat the water to just that temperature. If the engine stops and the supply of exhaust steam discontinues, we will see that we have a large mass of water heated to 212° fahr., and if there is a continuous load on the turbine the flow of steam through the turbine to the condenser will tend to make the pressure fall off slightly in the regenerator, and 212° fahr. will then be slightly above the boiling temperature of water at this lower pressure, so that the mass of water begins to give off steam and act like a boiler running at approximately atmospheric pressure. If, now, the engine starts again, steam will be delivered to the accumulator at a temperature slightly above that to which the water has fallen, due to the cooling effect of the evaporation of the steam for supplying the turbine, and the mass of water will again absorb heat from the exhaust steam.

In actual practice it is more convenient to run the regenerator at a pound or two pressure above the atmosphere, as in this case the piping is not under vacuum so that so much care does not have to be exercised to avoid air leaks. However, in certain cases, it is desirable to run below atmospheric pressure. In this way the power of the primary engine may be augmented by letting it operate at a partial vacuum. Plants are actually running with a delivery pressure to the turbines as low as six pounds below atmosphere.

Details of accumulator. The accumulator at South Chicago being quite a large one, is divided by a diaphragm in the middle into two decks, each deck having a series of flues similar to those shown in the small regenerator of Fig. 2. The steam generated in the lower deck passes up through steam flues into the upper chamber and passes out with the upper steam through the steam dome.

Water trap. There is a small percentage of the steam delivered to the regenerator which is condensed on account of radiation from the surface of the apparatus and this makes an accumulation of excess water in the regenerator and this is automatically discharged by the float trap, seen at the end of the regenerator. In most plants where such apparatus is used, there is more exhaust steam than is actually required for the turbines so that this condensation does not matter as it is only a small percentage anyhow. But in some plants, where the fullest possible amount of steam needs to be saved, the regenerators are lagged.

Water level. Gauge glasses are seen on each deck, and a series of valves and pipes are shown so that the water level in the upper deck can be set to suit that maintained in the lower deck by the float valve.

Reducing valve. If for any reason the primary engine shuts down for a considerable period, the supply of heat stored in the regenerator will become exhausted and the pressure will fall below a workable amount for the turbines. To take care of this condition, there is an automatic reducing valve which will be seen on the piping just above the scaffold. This valve in the present plant is set so that it will open whenever the pressure falls below atmosphere and deliver live steam through the reducing valve to the regenerator whenever the primary engine is shut down for a long enough period to make it necessary.

In this plant the relief valve is set for three pounds above atmosphere; in other words, whenever there is more steam than is necessary to run the turbine and heat the water in the regenerator to a temperature corresponding to its pressure, the excess steam will pass off to the air through the relief valve. On the other hand, if the engine does not give enough steam to supply the needs of the turbine, the reducing valve will open and let in enough live steam to make up the deficiency.

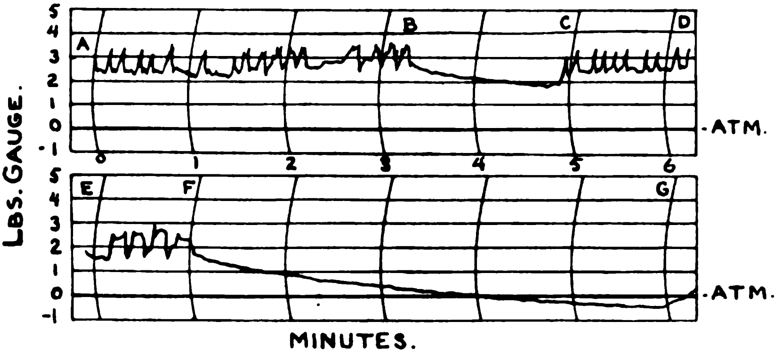

Fig. 5

Fig. 5 shows a typical chart from a recording pressure gauge on a regenerator operating from the exhaust of a roll-train engine. From *A* to *B* the engine is working and the pressure rises and falls as a function of the amount of steam delivered. At *B* the engine stops and the regenerator continues to deliver steam to the turbine so that the pressure begins to fall off down to the point *C*, where the engine begins rolling again. At *F* the engine stops again for a considerable period so that the pressure falls to atmosphere and a little below, until the point *F* is reached, where the pressure has fallen sufficiently to let the automatic reducing valve open and admit live steam, which brings the pressure back up slightly above the atmosphere.

At the Wisconsin Steel Company's plant, during normal operation, the pressure ranges about one or two pounds above atmosphere; when the engine is exhausting heavily it runs up to about three pounds. The lower limit of pressure, when the reducing valve opens, is about atmosphere.

As a matter of fact the regenerator is considerably larger than would be really necessary to regularize the flow of steam to the turbine, as tests show that under the ordinary load conditions, the regenerator will keep the turbine running at its average load for about seven minutes after the primary engine shuts down before the reducing valve opens. This would correspond to a period of about five minutes at full load on the turbine.

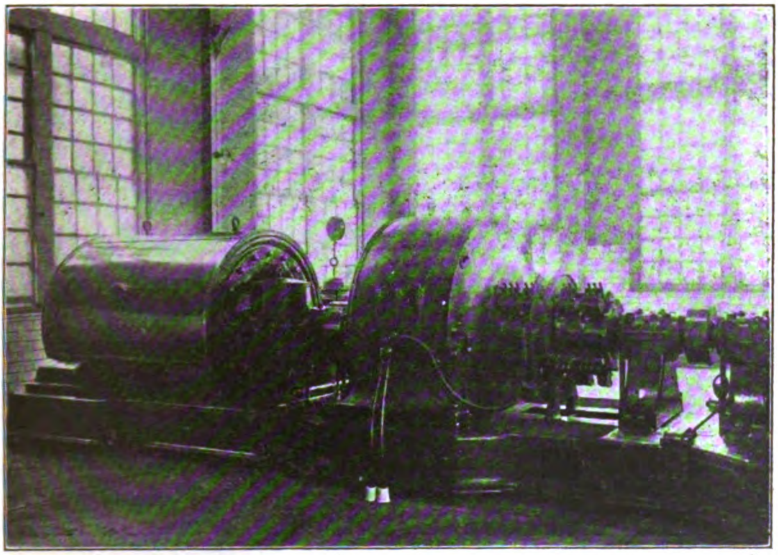

FIG. 6

Turbine. The turbine is of the well-known Rateau type, similar to those of the same character built in Europe, except that on account of American conditions it was necessary to make the construction heavier and stronger. The exterior of the turbine is shown in Figs. 1 and 6.

Wheels. The revolving wheels and their vanes are shown in Fig. 7. The wheels are turned out of solid steel plate with an increased cross-section towards the center to give them a large factor of safety.

Buckets. The buckets are made of a special alloy of great mechanical strength and rust-resisting qualities. Each bucket resembles a half of a brass shot-gun cartridge sawed in two. The buckets are held against the rim of the wheel by special rivets which have heads formed to fit the shape of the bucket at the bottom. It will be noted that this is an extremely simple and reliable method of securing each bucket independently of the others. The rivets are figured with a very large factor of safety, and there has never been a case of a rivet giving out in all of the large number of Rateau turbines which are running. The buckets are spaced at the periphery by a spacing or shroud-ring which serves to maintain an accurate spacing and acts as a baffle for improper currents of steam.

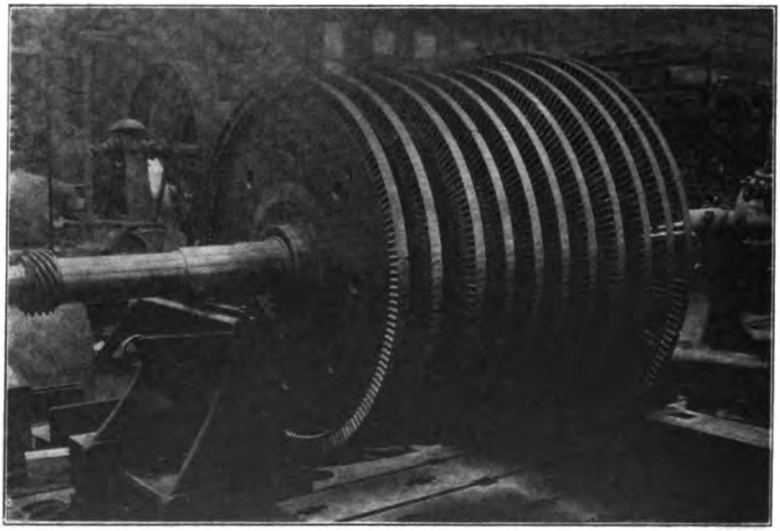

FIG. 7

It will be noted that these rings are made in several pieces. This is for the sake of convenience in manufacture and handling and does not materially affect the strength, as will be seen when it is remembered that at these high peripheral speeds a band of this character would have scarcely the requisite strength to hold itself as a hoop. On the other hand, the buckets must be depended upon to hold it as far as centrifugal force is concerned.

It is of interest to note that as the turbine is divided into so many stages, the steam velocities are very low, so that the impinging jets of steam do not wear away the entering edges of the buckets One of these turbines was examined after being in service for five years and it was found that the marks of grinding on the buckets were still visible, showing that the wear was negligible.

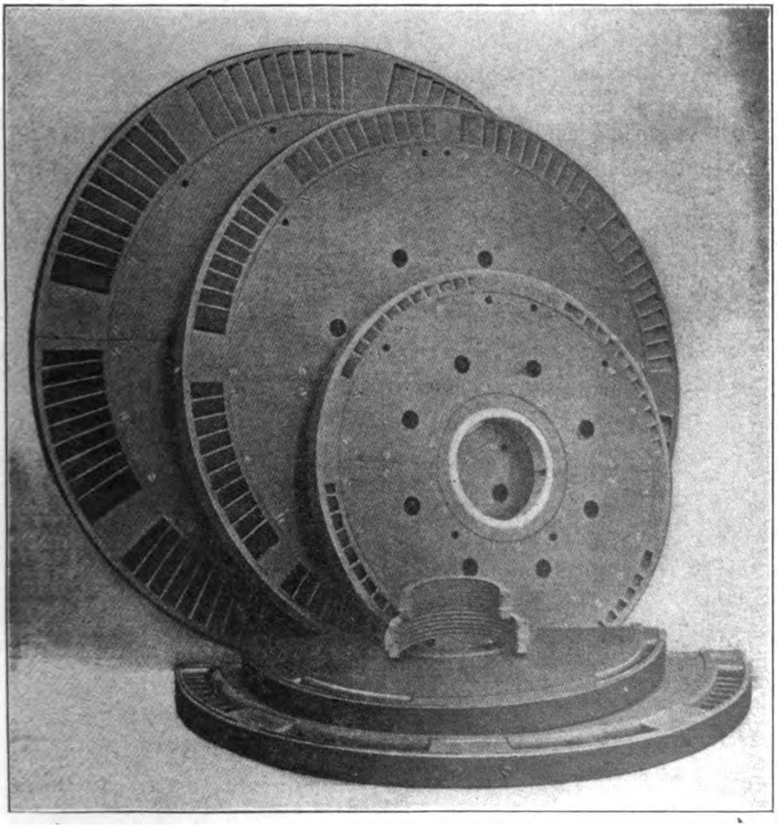

FIG. 8

Diaphragms. The Rateau turbines have fixed diaphragms which extend to the shaft between the wheels, forming a cell in which each wheel operates. There are no photographs of the diaphragms of this particular turbine, but they are of the same character as those shown in Fig. 8.

As the turbine is of the impulse type, the pressure is the same on both sides of the wheel and there is no tendency to leakage of steam through the clearance spaces around the periphery. These clearances can therefore be made as large as desired within reason, without having any material effect on the efficiency.

Governor. The governor is of the spring-balanced, fly-ball type, operating in connection with a dash-pot. It is located in the cylindrical casing on the turbine bearing seen in Fig. 6.

Throttle valve. The governor regulates the speed by throttling, the valve being of the double-beat type, located in the vertical cylinder seen in Fig. 1. Of course it will be realized that the steam admission pipe and the throttle valve have to be of abnormally large dimensions on account of the steam being delivered at such a low pressure.

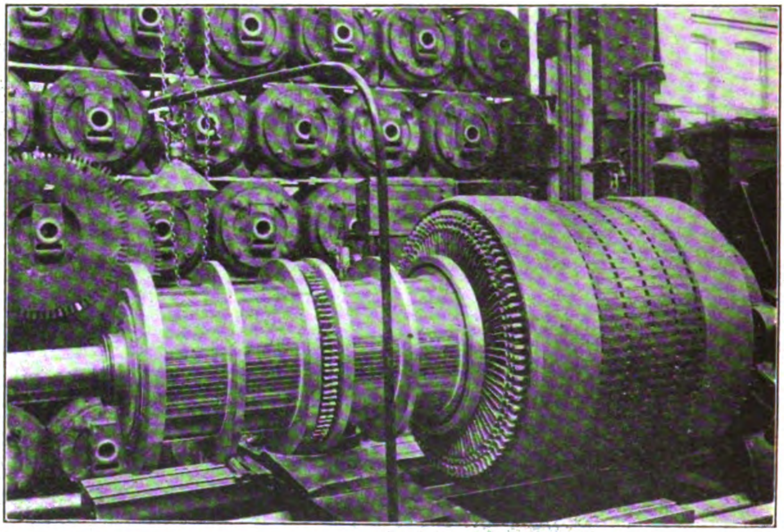

Fig. 9

The governor operates satisfactorily and maintains the speed within the ordinary ranges, either during violent or slow changes of load.

Bearings. The bearings are very simple in construction, as they are practically the same as the ordinary ring-oiled dynamo bearings, except that they have water-jackets to maintain the temperature at the desired value.

The turbine being of the impulse type, there is no end-thrust except that due to slight residual effects, so that only a few thrust-collars are necessary to locate the shaft and these are placed at one end of the governor bearing.

Stuffing-boxes. On low-pressure turbines the stuffing-boxes become a comparatively simple problem; on this turbine they simply consist of a water-seal in chambers bolted to the heads of the turbine.

Dynamos. One of the dynamos is shown in Fig. 6, the armature in Fig. 9, and the fields in Fig. 10.

The design of direct-current dynamos at turbine speeds is the really hard part of the engineering problem connected with such an installation. The turbine itself, being constructed entirely of strong materials, is relatively a simple matter in comparison with the dynamos. The centrifugal force at the periphery of the armature is nearly half a ton per pound of material, and it can be readily understood that the designing of a machine to hold a large number of small insulated coils with an adequate factor of safety, and so placed that they will stay where they are put and not unbalance the machine, is not a problem of the nature of child's play.

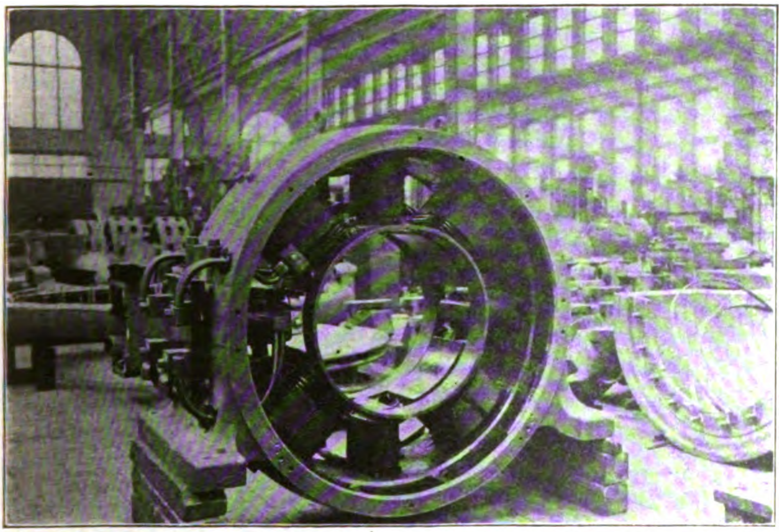

FIG. 10

When it was decided to put in this plant we found that direct-current dynamos of the speed and capacity required had not been built in this country and were not obtainable, so it was necessary for us to design the dynamos ourselves. It might also be remarked that although larger direct-current turbine dynamos had been designed in Europe, there were none, as far as we could find out, adapted to the requirements of American steel-mill practice.

In order to make the problem simpler and not run so much risk with abnormally long commutators, it was decided to divide the generating capacity into two direct-current units of 250 kw. each, the pressure being 250 volts.

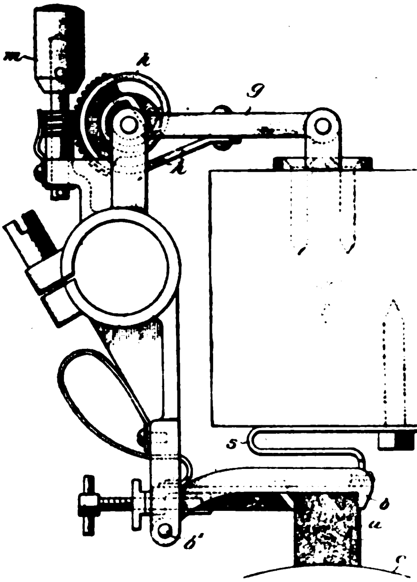

Fig. 10a

Armature. The armature resembles an ordinary iron-clad armature, except that everything has to be much stronger and the shaft at the center is very large so as to bring the critical speed well above normal. At the ends of the winding, where there are no teeth to hold the coils against centrifugal force, nickel-steel retaining rings are used, which give a very large factor of safety in spite of the enormous strains. These rings revolving in the fringe of the magnetic field from the pole-pieces would, of course, have a large loss in eddy currents generated in them and would overheat and cause loss in efficiency if something were not done to prevent it.

In Fig. 10, just outside the pole pieces will be seen iron rings which serve as magnetic shields to protect the retaining rings from the leakage flux which would otherwise pass through them. These rings of course increase the magnetic leakage of the fields by a small percentage but this can be allowed for once for all by providing a little extra material in the fields and, on the contrary, the shielding of the retaining rings prevents a loss which would be a continuous one during the operation of the machine.

Commutator. Abnormal peripheral speed limits the size of the commutator diametrically, and the great coefficient of expansion of long commutator bars limits the permissible length in a longitudinal direction. The commutator is therefore divided into two sections, as shown in Fig. 9, to avoid expansion troubles. The segments are held against the great centrifugal force by nickel-steel retaining rings which are shrunk in place and give a large factor of safety to the commutators. The two sections of the commutator are united by tangs resembling those ordinarily used at the inner end of commutators.

Fields. In order to overcome the effects of the very high commutating voltages caused by the large current and high speed, it is necessary to use commutating poles. These are well shown in Fig. 10. The rest of the field structure is of the same general character as ordinary machines. On the right of the field frame in Fig. 10 may be seen half of the turbine shell with the diaphragms removed.

Brush-holders. The brush-holders are one of the difficult features of the problem. I think it may be said that some brush holders are worse than others, but there are no perfect ones.

On these high-speed commutators the energy lost in the brush friction is usually a good many times that of the $I^2 R$ loss, so that it is important to keep the brush tension as low as possible. The other horn of the dilemma is that, unless considerable tension is maintained, it is difficult to keep the commutator absolutely true, and even one-thousandth of an inch eccentricity or a high spot will throw the carbons out of contact and make sparking and other troubles. On these machines the problem is handled in a very interesting manner by a novel type of brush holder, Fig. 10*a*. The carbons are held in a clamp swiveled some distance back of the point of contact, and between the carbon and the lead weight is located quite a stiff spring. The lead weight is held by this spring on one end and the swiveled arm at the outer end. A spiral spring adjusts the tension on the weight. The weight acts like the weight of a seismograph and the brush is therefore acted upon by a strong force tending to bring it back in contact if for any reason it has a tendency to be thrown off the commutator by a high spot or otherwise. On the other hand, the adjusting spring behind the weight enables the maintenance of a low average tension on the brush. In this way the natural period of vibration of the brush and its spring acting against the weight can be made a number of times the frequency of revolution. Care must, however, be taken that the natural period of vibration of the inertia weight, vibrating on the inner and outer springs, shall not be such that resonance will be caused by the frequency of rotation.

Ventilation. These high-speed machines cause a considerable whirring noise on account of high peripheral speed, and for this and other reasons the frames are enclosed with end-bells. On the end of the armature in Fig. 9 will be seen the projecting tips of fan-blades which are mounted on the armature. These draw in air through a passage at one end of the frame and force it through the machine down through a passage at the other end and out through the base. This assures adequate ventilation and makes the machines comparatively quiet in operation.

Operation. The general operation of the machines, as regards heating and sparking, is about the same as with ordinary slow-speed dynamos, although it is usual to have slightly higher temperature rises on the high-speed machine, because the losses are concentrated in such small space that it makes the ventilation of abnormal proportions to get down to the limits which are sometimes specified for slow-speed machines.

Regarding the sparking, it may be said that these high-speed machines are quite sensitive to the condition of the commutator surface, as dirt or other causes which tend to keep the brushes out of contact will induce sparking. Sometimes the same cause would not have the same effect on slow-speed machinery. In general it may be said that there is not a great deal of difference in the operation of slow- and high-speed machines.

These machines being equipped with commutating poles, with which the forces to accomplish commutation increase proportionately to the load, have an advantage as compared with ordinary machines in handling temporary overloads, as will be seen from the fact that we have a number of times carried the entire load on one machine for several hours while the other dynamo was running idle.

Condenser. The condenser and air pump are of standard type. It may be remarked that there has been no difficulty in maintaining a good vacuum in normal operation and that the plant is usually run at a vacuum of about 28 inches.

Tests. The tests of the plant have already been referred to. Table 1 gives the details of the observations. Fig. 11 shows a curve of the steam consumption of the turbine per electrical horse-power at the switchboard. The steam consumption was determined by temporarily putting a Venturi meter in the pipe delivering the condensing water to the condenser and measuring the temperature of the entering and discharged water, in this way using the condenser as a calorimeter to determine the heat rejected from the turbine. It may be well to point out that in order to get suitable temperature ranges and on account of other local conditions obtaining at the time of the test, the vacuums were not as high as the turbine was designed for, so that although the steam consumption was better than the guarantees, the values given do not represent the actual capabilities of the turbine.

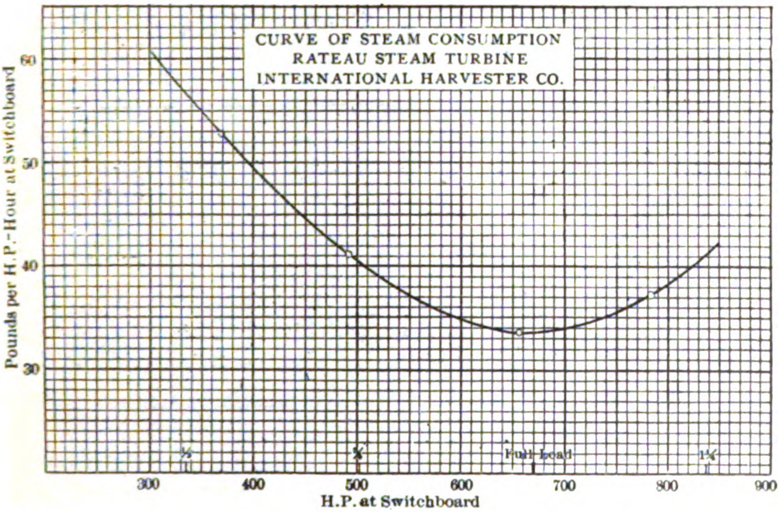

FIG. 11 CURVE OF STEAM CONSUMPTION OF TURBINE

FIG. 11

Comparative power of low-pressure turbines. To those not familiar with low-pressure turbines, the query might naturally arise as to how it comes that the low-pressure turbine can get

TABLE I.—RESULTS OF TESTS OF 500-KILOWATT INSTALLATION OF RATEAU TURBINE, STEAM REGENERATOR AND GENERATORS, AT THE SOUTH CHICAGO PLANT OF THE INTERNATIONAL HARVESTER COMPANY

OBSERVED AND DERIVED VALUES	UNIT	TEST NO. 1	TEST NO. 2	TEST NO. 3	TEST NO. 4
Date of trial	1907	Mar. 11	Mar. 11	Mar. 12	Mar. 12
Duration of trial	hours	1.00	2.00	2.00	2.00
CONDENSER					
Average head on Venturi meter	inches	3.48	7.57	14.72	17.77
Average initial temp. of condensing water	° fahr.	38.40	39.30	38.90	39.55
Average final temp. of condensing water	° fahr.	80.00	68.30	61.50	66.55
Average rise of temp. of condensing water	° fahr.	41.60	29.00	22.60	27.00
Average condensing water per min	cu. ft.	151.9	192.8	247.2	295.4
Average condensing water per min	pounds	8,155.0	12,030.0	16,750.0	18,700.0
Average barometer	inches	29.6	29.6	29.2	29.2
REGENERATOR					
Average pressure at turbine, abs	pounds	16.9	16.6	15.9	15.3
Average temp. of steam at turbine	° fahr.	215.5	217.0	216.3	213.2
Average temp. of air	° fahr.	48.0	48.0	64.0	64.0
Average steam delivered per hour	pounds	19,500.0	20,220.0	22,050.0	29,280.0
TURBINE					
Average pressure above controlling valve	inches	32.9	32.4	30.93	29.75
Average pressure under controlling valve	inches	18.6	19.0	21.47	24.85
Average vacuum at exhaust casing	inches	25.31	26.6	26.95	26.40
Average revolutions of turbine ± 15 per min	r.p.m.	1,540.0	1,540.0	1,500.0	1,500.0
Average brake hp. at turbine shaft	hp.	409.0	544.0	727.0	869.0
GENERATORS					
Average ammeter readings	amperes	1,085.0	1,485.0	2,195.0	2,482.0
Average voltmeter readings	volts	245.2	246.9	233.5	238.3
Average current delivery in kilowatts	kilowatts	266.1	366.7	489.2	591.6
Average efficiency of generators	per cent.	90.2	90.2	90.2	90.2
Average hp. at the switchboard	hp.	369.0	491.0	656.0	784.0
DERIVED RESULTS					
Radiation from piping per min	B.t.u.	2,700.0	2,700.0	810.0	810.0
Heat equivalent of work done per min	B.t.u.	17,490.0	23,250.0	31,100.0	37,300.0
Heat delivered to condensing water per min	B.t.u.	339,100.0	349,000.0	395,100.0	498,100.0
Steam per min. to turbine	pounds	326.0	337.0	367.5	488.0
Steam per kilowatt-hour	pounds	73.3	55.2	45.2	49.5
Steam per hp. at switchboard per hour	pounds	52.8	41.2	33.6	37.3
Steam per brake hp. at turbine per hour	pounds	47.7	37.1	30.7	33.7

so much power out of the exhaust steam. It is quite inconvenient to show this by the ordinary pressure volume diagram, Fig. 12, but this diagram readily shows the difficulty of trying to make a piston engine utilize the expansion of the steam down to the volume realizable with the good vacuums maintained with turbines. The diagram is laid out showing the expansion of 4.21 pounds of steam, which is the average amount of steam used per stroke in the primary engine. The dotted curve shows the volume in cubic feet of this amount of steam expanding without condensation from 140 pounds gauge to atmosphere and from there down to a vacuum of something less than 28 inches, the 28-inch point being considerably off the scale of the diagram. The upper cross-hatched portion represents the adiabatic expansion of the steam down to atmospheric pressure and the lower cross-hatched portion, the expansion from atmosphere adiabatically to 28 inches vacuum. It will be seen that the areas of the diagrams, which show the theoretical power in the steam, are approximately equal.

The theoretical steam consumption of a perfect heat engine working between the limits of the absolute initial pressure P and the absolute exhaust pressure p, is given by the following formula:

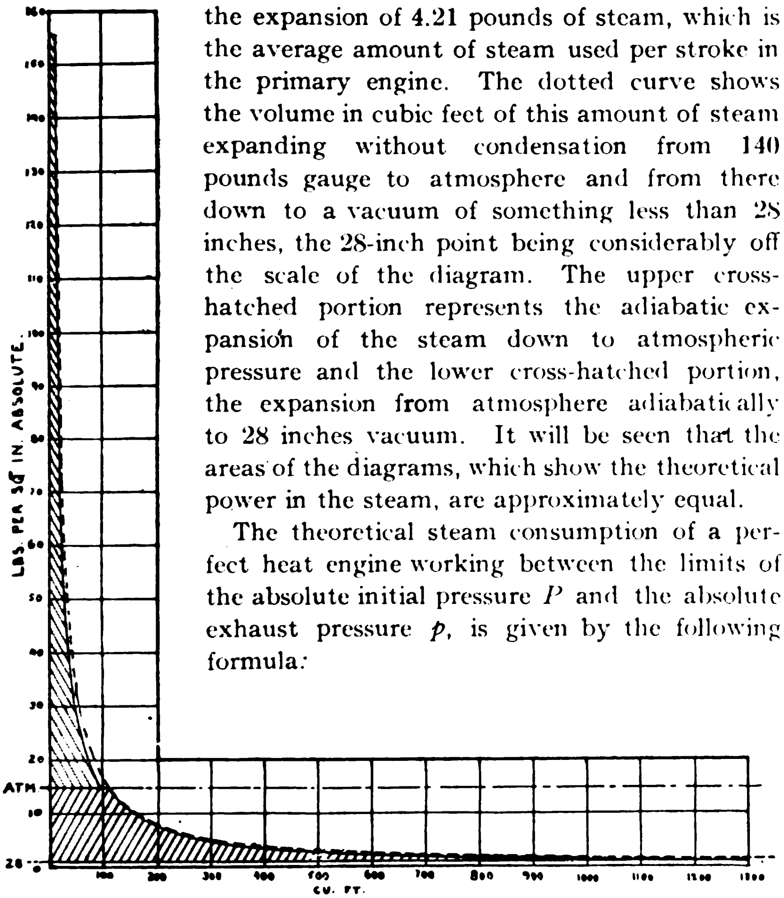

FIG. 12

$$K = 0.85 + \frac{6.95 - 0.92 \log_{10} P}{\log_{10} P - \log_{10} p} = \text{kg. per hp-hr. for metric units}$$

$$\text{or } K = 1.9 + \frac{17.91 - 2.05 \log_{10} P}{\log_{10} P - \log_{10} p} = \text{lb. per hp-hr. English units.}$$

If from this we work back and find the pressure at which a perfect heat engine would have to operate in expanding from boiler pressure down to atmosphere in order to consume the same amount of steam as a perfect engine or turbine working from atmosphere down to 28 inches vacuum, we find that the initial pressure would be about 140 pounds.

The temperature-enthropy diagram shows this much better than the pressure-volume diagram. In Fig. 13 the upper cross-hatched area represents the energy available in expanding one unit of steam adiabatically to atmosphere, while the lower area shows the available energy in expanding a unit of steam from atmosphere down to 28 inches vacuum. It will be seen at a glance that the energy available in each case is the same.

Further than this, the low-pressure turbine is usually a more efficient heat engine than the primary engine; that is, it turns out a greater percentage of the power theoretically available. Thus it will be seen from the tests that the turbine in this case consumed less than 35 pounds of steam per horse power delivered at the switchboard, while the primary engine consumed 54 pounds per indicated horse power.

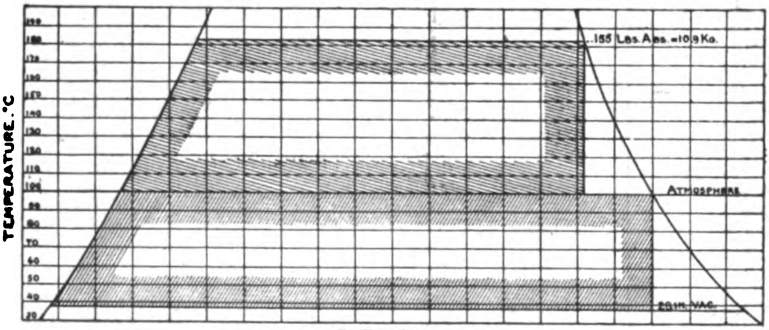

FIG. 13

Condensing engines. The query also arises how the exhaust steam-turbine plant compares in economy with the primary engine running condensing.

In the first place, it introduces operating difficulties to run reversible engines of this character condensing. Nevertheless, they are being operated this way in a number of instances. We understand that a steam consumption of 25 pounds per indicated h.p.-hour is the best that can be obtained on a compound reversible condensing mill engine and that when the losses in clearances, condensation, and mechanical efficiency are taken into consideration, the steam consumption horse power at the shaft would come up to at least 38 pounds.

In comparison we can take the low-pressure turbine plant at the Wisconsin Steel Company as an example. The primary engine delivers to the regenerator an average of 52,400 pounds of steam per hour and develops 1010 indicated horse power. The tests on the turbine showed that it took 33.6 lb. per electrical horse power-hour. This would make available at the switchboard 1560 hp. or a total of 2370 hp., after deducting the engine friction; that is, 22.1 lb. of steam per total horse power at the shaft as against 38 with the condensing engine. In other words, the condensing engine would take about 70% more steam per effective horse power than the combined high-pressure engine and turbine; this result is checked by the experience at the Poensgen Steel Works at Dusseldorf, in which various engines of the plant were connected to a central condensing system which effected a saving of 15% in the amount of steam used. Afterwards one of the Rateau steam regenerator plants was installed, and the exhaust steam put through the turbines. The saving now exceeds 40% as compared with the average of a 15% saving by running all their engines into the condensing system.

The saving in this case is not as great as the example we have just cited, because the engines are not all reversible and are consequently more economical to start with.

In general, it will be found to work out that the combination of a low-pressure turbine with a high-pressure engine is a more economical unit than a condensing engine alone; and it frequently figures out to a lower steam consumption than a high pressure and low-pressure turbine or a high-pressure condensing turbine.

Degree of vacuum. An interesting problem in connection with these plants is what degree of vacuum is most economical. Where the admission pressure to the turbines is so low, the steam consumption is affected to a greater percentage by the vacuum than with high-pressure turbines. In Fig. 14, the Curve *T* shows the theoretical steam consumption per horse power of a perfect heat engine working between an admission pressure equal to atmosphere and an exhaust pressure of the various inches of vacuum set down as abscissas.

The actual steam consumption per brake horse power would be as indicated in Curve *A*, assuming a constant efficiency of the turbine over the range of the curves. This assumption is not strictly correct but is near enough so over the region of the minimum point which is what we are concerned about. It is seen that both the theoretical and actual consumption decrease very rapidly with a better vacuum, so that, for example, about 25% more power can be obtained from the same amount of steam by running at 28 inches vacuum as compared with 26 inches. On the other hand, it will be found that the horse power required to run the circulating pump and the other auxiliaries increases at a very rapid rate with the higher vacuua, although the power of the air pump decreases slightly.

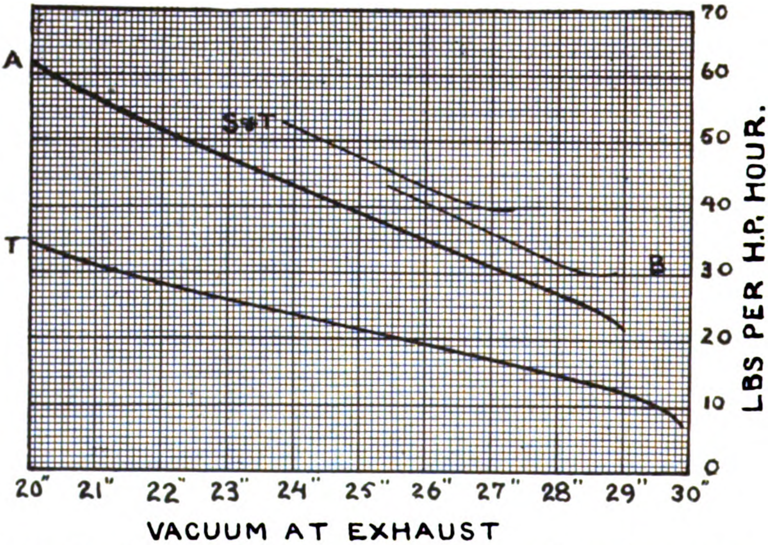

FIG. 14—T = Theoretical consumption of perfect engine per horse power-hour. A = Actual consumption of turbine per brake horse power-hour. B = Actual consumption of turbine per net electrical horse power-hour with barometric condenser after deducting power for auxiliaries. S and T = Consumption per net electrical horse power-hour with surface condenser and cooling tower after deducting power for auxiliaries.

In order to show the effect of the power consumed in the auxiliaries, we have taken as an example such a turbine operated in connection with a barometric condenser and assumed that the circulating pump and air pump were motor-driven by current supplied from the dynamo connected with the turbine. This would not ordinarily be the method of arranging such a plant, as the turbine depends on the vacuum as its source of power and it is inconvenient to get the plant started; but such an example offers a clear way for figuring the net output of the plant.

The Curve *B* shows the pounds of steam per net electrical horse power, the power for operating the auxiliaries first having been deducted. This curve is on the basis of circulating water at 70° fahr., (which can be taken as representing average conditions) and the usual commercial forms of condenser auxiliaries. It will be noted that the curve begins to turn up at the higher vacuua instead of turning down as do the theoretical curve and the actual gross consumption curve.

In steel mills there is usually a large water system for supplying the plant, and it is generally thought best to avoid complication and supply the condensing water for the turbine plant directly from the system, without installing a separate circulating pump. The head of the water systems is usually in the neighborhood of four times the head required for the circulating pump. This extra amount of power, although not needed for the turbine plant, has to be considered in determining the most economical vacuum and has the effect of shifting the minimum point to something over half an inch lower vacuum than indicated on Curve *B*.

Where condensing water is not available, a low-pressure turbine plant can be installed in connection with a cooling-tower equipment.

Curves *S* and *T* show the steam consumption per net electrical horse power in a plant equipped with a surface condenser and cooling tower, after deducting the power which would be consumed in motor-driven air, circulating and hot-well pumps, and in the cooling-tower fan. This curve is made out on the basis of 75° temperature of the air and 70% humidity, which are taken as representing average conditions. It will be noted in this case that the most economical vacuum is practically the maximum vacuum obtainable under the conditions.

With the barometric Curve *B*, it will be noted that a higher temperature of the circulating water would move the most economical point to a lower vacuum and vice versa.

These curves are on the basis of machinery of the character under consideration. It would be well to point out that with larger turbines and with alternating-current generators, the efficiency of the generating set and also that of the auxiliaries would be increased so that the points of minimum net consumption would be shifted downwards and slightly towards the right.

These values refer to steam consumption and the real point in most cases is the minimum cost of current. The cost of current in such a plant is almost entirely represented by the interest on the investment and other fixed charges. The intrinsic cost of both the turbine and the condensing equipment increases with the higher degrees of vacuum so that these factors would tend to shift the point of minimum cost of current a slight amount to the left.

Practical results. The general result of the installation of this low-pressure turbine equipment is that it enabled the mill to shut down the two 250 kilowatt engine-driven generators which formerly operated the mill, and for a long time the turbine carried the entire electrical load of the steel mill, operating from the exhaust of the blooming engine and not taking any live steam except during abnormal stoppages of the blooming engine.

Recently they have installed some electrical unloading machinery on their docks. When this machinery is all in operation the load frequently runs up above the ultimate capacity of the turbine and they have to start up one or more of the engines and run in parallel with the turbine.

The attendance and lubrication items for the turbine plant are very small. The turbine is located near the blooming engine, while the other generators are located in the blowing engine house about a quarter of a mile away. There is but one attendant on duty in the turbine engine room.

At this plant the boilers are supplied principally by gas from the blast furnace, but the supply of gas is quite variable and usually not adequate to give all the steam required, so that more or less coal has to be used. The installation of the turbine, therefore, results in a saving of the coal corresponding to the steam required for operating the dynamo engines. This, as indicated above, is quite a variable quantity but has been variously estimated at from $10,000 to $20,000 per year. In figuring on the installation of the turbine plant, it was estimated that the turbine would effect a considerable saving, even if the supply of gas were generally adequate, as the maintenance of the turbine plant would be considerably less than the corresponding engine and boiler plant, or even a gas-engine plant.

Further, it is well to remember that exhaust steam passing to the atmosphere can be looked upon as the equivalent of a water-power plant and that it usually has the advantage of being near a market for power, besides costing less to develop than a water-power plant would. In other words, the exhaust-steam plant should be able to produce the power cheaper than a corresponding water-power plant.

Cost of power. During three months when the steel plant was running at nearly full capacity, the turbine delivered an average of 188,300 kw-hr. per month, or 51% of the total possible kilowatt-hours if run at its rated load the entire time.

The operating expenses are at the following rates, based on the above output:

Oil, waste etc.	0.002	cents per kilowatt-hour
Attendance	0.074	" " " "
Maintenance and miscellaneous	0.011	" " " "
Total operating	0.087	" " " "
Fixed charges	0.212	" " " "
Total cost	0.299	" " " "

The fixed charges are figured on the basis of a cost of $80 per kilowatt. This figure would, of course, vary considerably with the conditions, but it can be taken as an average for moderate-size plants. Interest, depreciation etc. are allowed for at 12%. Nothing is allowed for superintendence, as no additional force is required for this item.

The cost being made up so largely of fixed charges, it varies very markedly with the load-factor. In fact, if the plant is run 24 hours a day, the lubrication, attendance, and maintenance are only affected to a slight extent by the amount of load, so that they have almost the same effect as a fixed charge. Of course if the plant were run only during the day shift, the operating expenses would go down.

The effect of the load-factor on the cost is seen in Fig. 15, the load-factor here being taken as the ratio of the actual output, divided by the output if run the entire time at rated load.

Metallurgical operations. It will be noted that the cost of power at the larger load-factors is extremely low and would be even more so in a larger plant where the first costs and the other costs would go down considerably.

If the exhaust steam turbine plant were used for electric smelting or similar purposes, it is probable that the load-factor could be kept up over 80%, which, we see from the curve, gives a cost of 0.19 of a cent per kilowatt-hour.

It might be remarked that the electric smelting processes take, on a very crude average, one kilowatt-hour per pound of metal produced. It will therefore be seen that such plants offer a good opportunity for doing certain kinds of metallurgical or similar work.

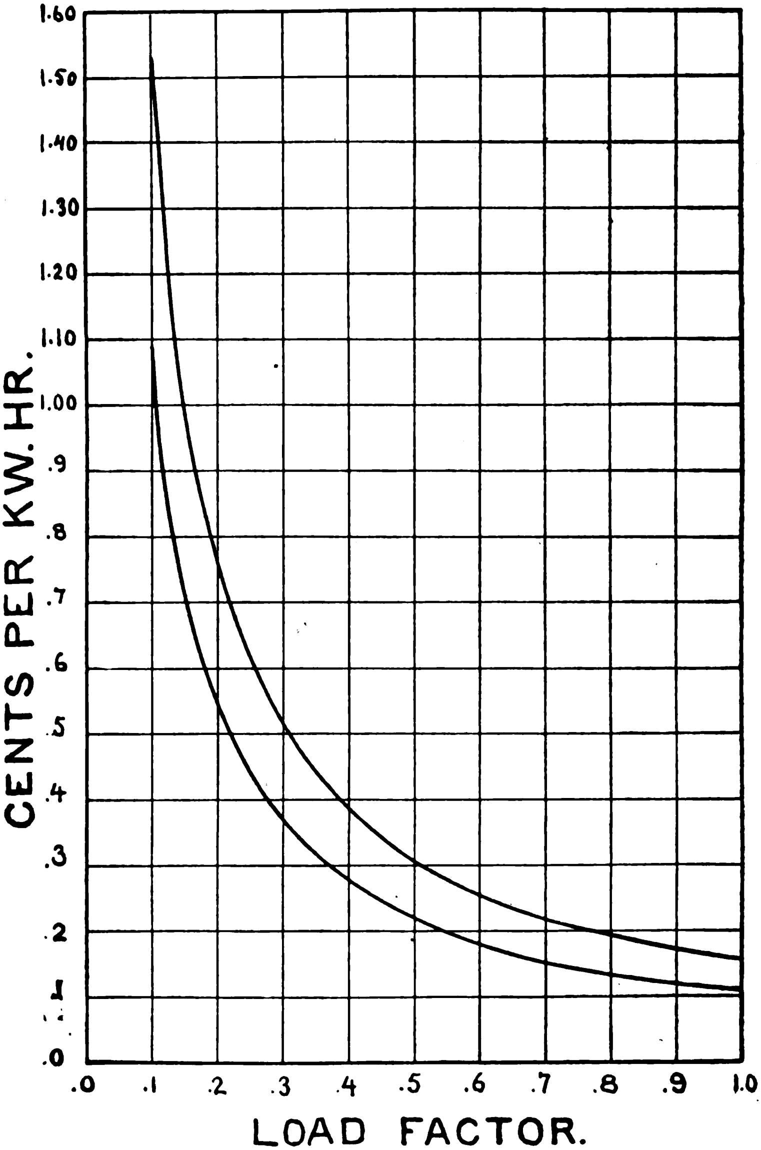

FIG. 15

In the foregoing no value has been assigned to the exhaust steam. In most places where such exhaust steam occurs, there is not a good opportunity to utilize any considerable portion of it in any other ways, so that it would otherwise be a waste product. In case of selling power, it will be seen that either the steam itself or the current produced could be profitably sold to outside parties.

Under these conditions the question of the continuousness of the power would arise. Of course when the primary engine shuts down for more than a few minutes, there is a tendency for the boilers to blow off at the safety valve, so that for short periods it does not mean any more fuel, even if the primary engine is stopped. If the primary engine is stopped altogether, the boilers stand ready to furnish the steam to the turbine and the latter would consume approximately the same amount of steam as non-condensing engines would. If this condition of running with live steam were one that would occur for a considerable time, it would be advisable to install a mixed high-pressure and low-pressure turbine; that is, one which would have a high-pressure section which is automatically fed with high-pressure steam whenever this becomes the normal source of steam. Such plants as this are already operating in a number of places where the primary engine runs only during a day shift and it is necessary to have the electric power day and night.

Field of usefulness. The foregoing remarks apply more particularly to the conditions in a steel plant, but similar conditions occur with large mining hoists; of course any other source of exhaust steam, whether intermittent or not, can be utilized in similar fashion. It has been already pointed out that a great saving can be effected in connection with continuous running engines, and that such a system can be used to increase the power of such engines and that, even when run condensing, the power and total economy can sometimes be increased by combining a low-pressure turbine and engine.

A paper presented at the 223d Meeting of the American Institute of Electrical Engineers, New York, December 18, 1907.

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(Subject to final revision for the Transactions.)

A NEW CO_2 RECORDER.

BY C. O. MAILLOUX.

In the very valuable paper on "Power Plant Economics," presented before this Institute, Jan. 26, 1906, by Mr. H. G. Stott, (Trans. Vol. XXV, pp. 1-27), attention was called to the utility of records of the percentage of CO_2 (carbonic dioxide) present in the flue gases of a boiler plant, as a means of determining and of preventing those fuel losses which might be termed "avoidable".

Mr. Stott's paper contains curves and data which show quite conclusively that there is an important and close relation between fuel-economy and the percentage of CO_2 contained in the flue-gases. In analyzing the average loss incidental to the conversion of the energy of a pound of coal into electrical energy, he finds, in the case of one of the most efficient plants in existence, that the "loss to the stack" amounts to 22.7 per cent. It is well known that in the majority of cases this loss exceeds 30 per cent. Mr. Stott refers to a case where the loss was approximately 40 per cent. of the thermal value of the coal. The utility of CO_2 records, as a means of locating the "leak", in a case of this kind, is made apparent by the following statement, quoted from Mr. Stott's paper:

"Fig. 2 shows what improvement may easily be obtained by watching the CO_2 records, and indicates a saving of about 19 per cent. over the previous case."

In the time which has elapsed since the reading of Mr. Stott's paper, the importance of "watching the CO_2" has been demonstrated in hundreds of cases, here and abroad, in a manner which no longer leaves room for doubt. As an example of a recent appreciation of the utility of complete knowledge of the CO_2, in flue-gases, the following emphatic statement is of interest:

"It cannot be too strongly impressed upon the power-plant owner that CO_2 is the factor upon which depends his very existence under any circumstances of real competition".

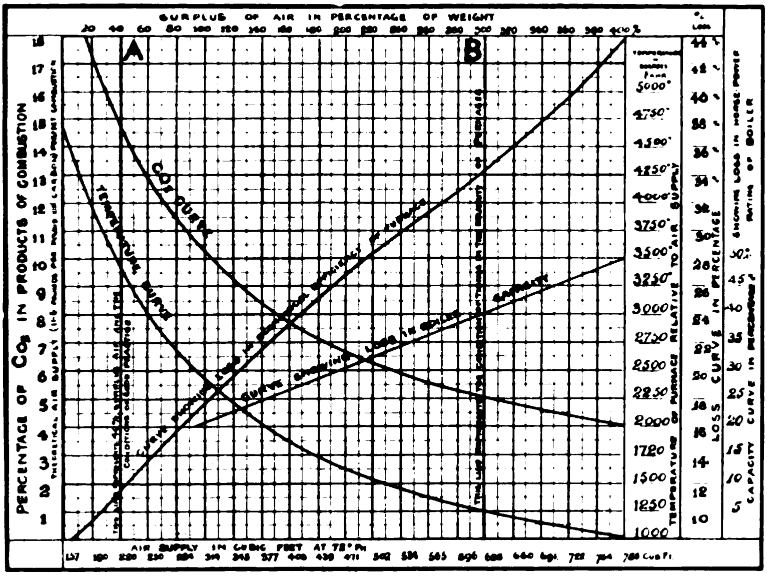
This statement is made by Mr. W. D. Ennis, a leading authority on fuel-economy. It is quoted from the *Engineering Magazine* of June, 1907, containing the first of a series of articles by him, on "Efficiency in Fuel Burning", in which the entire subject is treated exhaustively. Many other citations to the same effect could be made. These will suffice to demonstrate the desirability of CO_2 records, and of satisfactory apparatus for obtaining such records, in the boiler room. Incidentally, they call attention to two sources of reliable information regarding the scientific (chemical and physical) principles on which the value of the percentage of CO_2 as a criterion of the efficiency of a steam boiler depends.

It is not within the scope of this paper to enter into a detailed discussion of these principles. For our purpose, a sufficient idea of these principles and of their consequences may be obtained from the graphical "summary" or "resumé" of them indicated by the curves in Fig. 1, which were prepared and kindly placed at the disposal of the Institute by Mr. H. J. Westover, the inventor of the present CO_2 recorder. The ordinate values of the different curves, at the points where these curves intersect the vertical line *A*, when interpreted by reference to the proper scales of values, represent the condition of "good" practice. The vertical line *B* marks, in the same way, the conditions of "bad" practice.

The average working conditions and the economic results attained, in the majority of steam plants, are such as would correspond to a characteristic vertical line located somewhere between the vertical lines *A* and *B*—as a rule, nearer *B* than *A*. In a few "glorious" examples, that characteristic line is at the *left* of the line *A*. In many "horrible" examples it is at the *right* of the line *B*.

We see, at a glance, in Fig. 1, that high efficiency corresponds to high percentage of CO_2, in the flue-gases. We also see that the falling off in percentage of CO_2 and in the fuel efficiency, is due primarily to *excess* of air. From this, it becomes obvious that the percentage of CO_2 present in the flue-gases, being influenced directly and solely by the conditions of combustion of the fuel, can serve as a criterion of the performance and efficiency of the boiler plant, and as a means of detecting defects and of suggesting improvements in its operation.

This has been known more or less generally, for a long time, and it has been the practice of many experts to make chemical analyses of the flue-gases in connection with boiler tests. The oldest and most widely known form of apparatus used for this purpose is that of Orsat. Since a knowledge of the principle of this apparatus will be of assistance in understanding the operation of a new form of CO_2 recorder to be herein described, a brief reference to it will be made.



Ex CO_2 14¾ shows 36% surpluss air with 11½% loss representing 88½% furnace efficiency

CO_2 5 shows 300% surplus air with 34½% loss representing 65½% furnace efficiency

THE DIFFERENCE BETWEEN USUAL AND GOOD PRACTICE IS 22½%

FIG. 1

The Orsat apparatus is represented diagrammatically in Fig. 2. The movable vessel *E*, of glass, containing water, is connected by a flexible (rubber) tube, *F*, with a stationary vessel *G D*, of glass, of the general form shown, having graduations at the upper part of the tubular portion *G*, and connecting, by a small tube, *C*, with a three-way coupling in which are valves or stop-cocks, *A*, *L*, and *M*. The cock *L* controls a connection leading to a receiving vessel *H*, filled with small glass tubes, and connected, at the bottom, by a bent tube, with a supplemental receiver, *I*, which is open to the atmosphere, at the top. The

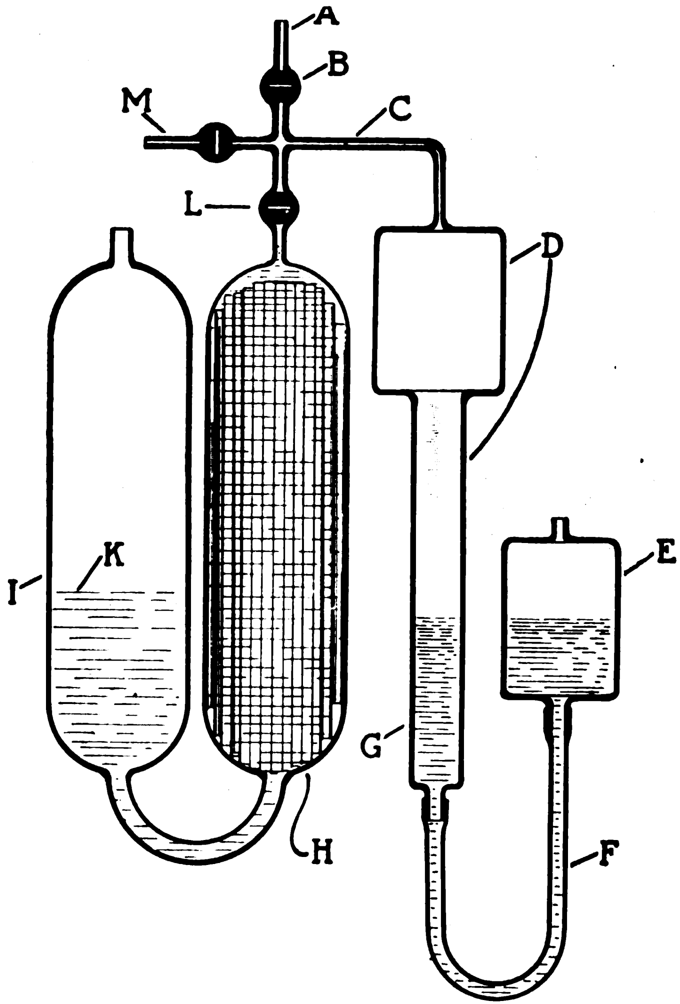


Fig. 2

liquid put in the vessels *H* and *I* depends on the particular gas which is to be analyzed. When the apparatus is to be used for determining the percentage (by volume) of CO_2 in flue-gases, the liquid put in these vessels consists of a solution of caustic soda, or caustic potash. The process of making an analysis comprises various manipulations which must be made in proper order, with a certain care, each requiring a certain time. The cocks *M* and *L* being both closed, the cock *B* is opened, leaving a free passage from the receiver *D* to the atmosphere. The movable vessel *E* is then raised, causing the level of the liquid to rise in the vessel *G* and the liquid to fill the portion *D* as far as the small tube *C*. The cock *B* is then closed, and the cock *M*, controlling the connection with the supply of gas, is opened, allowing the gas which is to be analyzed to enter. The vessel *E* is now lowered; and the gas enters and fills the vessel *D* and a part of the vessel *G* as far as desired. The exact quantity of gas allowed to enter is controlled by the position of the movable vessel *E*, which is adjusted carefully, so as to bring the level of the liquid in *G* to a certain mark, corresponding to a definite volume, say 100 c.c. of gas. The cock *M* is then closed and the cock *L* is opened. The vessel *H* is normally left filled with the absorbent liquid, at the end of the preceding test. Therefore, on opening the cock *L*, this liquid begins to fall, in *H*, and the gas begins to enter. The movable vessel *E* is now raised again until the gas has been entirely forced out of the vessel *D* by the rise of the liquid in *G* and *D*. The gas enters the vessel *H*, forcing down the absorbent solution, which is displaced into the vessel *I*. The glass tubes in the vessel *H* present a greatly increased surface, wet with the caustic soda or potash solution, whereby the chemical reaction on which the analysis depends is expedited. This reaction is the absorption of the CO_2 gas contained in the sample of gas forced into the vessel *H*, and its combination with the soda or potash contained in the solution, to form a "carbonate", of soda or potash, which remains in solution. The volume of the gas in the vessel *H* is diminished in proportion to the amount of CO_2 abstracted from it by this chemical reaction. After a certain time, sufficient for the reaction to be practically ended, the movable vessel *E*, which was held at its upward position during the time allowed for the reaction to take place, is lowered, causing the residue of gas to return into the vessel *D*. The vessel *E* is lowered until the liquid in *H* rises and fills the vessel to the top as far as the cock *L*. If the sample of gas contained no CO_2, it will not have been reduced in volume when it returns into the vessel *D*; and the level of the liquid in this vessel will be at the same mark as it was before the gas was sent into the vessel *H*. If the gas contained CO_2, the volume returned from *H* to *D* will be smaller than it was before; consequently, when the "residue" has all passed out of *H*, the liquid in *G* will stand at a higher mark than before. Suppose, for example, that the initial volume was 100 c.c. and that the residual volume is found to be 92.5 c.c. Then, the percentage (by volume) lost, in passing through the vessel *H*, was = 100 – 92.5 = 7.5 per cent. Since the loss in volume was due to the absorption of CO_2 only, it follows that this sample of gas contained 7.5 per cent. of CO_2. If the residue is not to be subjected to further analysis, the cock *B* is opened and the gas is forced out at *A*, by raising the movable vessel *E* and filling the vessel *D*, as before. If it be desired to analyze the residue for some other gas, say oxygen, for example, the pipe *A* is connected with another vessel similar to the vessel *H* and containing a chemical reagent which can absorb the gas whose percentage is to be determined. The reagent used for the oxygen analysis is pyrogallic acid dissolved in a solution of caustic potash. The operation is conducted in substantially the same manner as for the estimation of the percentage of CO_2. The residue of gas is returned to the vessel *D*, its volume is measured, and the loss of volume, if any, is noted, as before. Suppose the volume be now found = 90 c.c. Then the percentage of oxygen which was present in the gas was 92.5 – 90 = 2.5 per cent. A third analysis may serve to determine the percentage of CO (carbon monoxide), present in the sample. The reagent then used is cuprous chloride, dissolved in hydrochloric acid. The residue left after this determination will be substantially all nitrogen. From the data thus obtained it is possible to determine the percentage of CO_2, O, CO, N, and of air, contained in the flue gas.

Various other forms of apparatus for gas analysis have been devised and are known under different names, such as the apparatus of Wilson, Elliott, Hempel, etc.

(Further details and also some bibliographical references concerning methods of flue-gas analysis will be found in Carpenter's "Experimental Engineering", Chapter XIV.)

These different forms of apparatus are all, in reality, transplantations from the chemical laboratory, modified and simplified as far as practicable, to render them more transportable, and more suitable generally, for the purposes of flue-gas analysis. They are only intended and, obviously, would only be suitable, for the purpose of making a few analyses at a time, under "laboratory" conditions.

In order that the results of flue-gas analysis may be of service in the operation of a steam boiler plant, it is necessary that these analyses should be obtained under conditions which satisfy certain indispensable "practical" requirements, including the following: 1st, the apparatus should work automatically, without more care and attention than any ordinary apparatus of "mechanical" character;

2d, it should give results (analyses) quickly and regularly;

3d, it should give a visual indication and record of all the results.

For the purposes of information and guidance, in regard to the economic operation of an average boiler plant, it is not necessary that analyses should be made of *all* the constituents of the flue-gases. This would require a too much complicated apparatus, and would lengthen too much the time required for each operation. Practically, the determination of the percentage of CO_2 is all that isrequired.

Various forms of automatic CO_2 recorders which meet the above requirements more or less satisfactorily, have been devised and have been put into commercial use, during the last three or four years. Although some of these CO_2 recorders have done and are still doing good work in many cases, their applicability and usefulness in other cases have been restricted by the presence of conditions and the absence of features which rendered modifications and improvements very desirable.

The present CO_2 recorder, which has recently been perfected, is the result of careful analysis of all the requirements and of a critical study of the weak points and drawbacks of all the preceding forms of CO_2 recorder. The new features especially desirable from the point of view of the boiler room manager are: 1st, to make the apparatus more "rugged" mechanically. and, consequently, less liable to break down or derangement from mechanical causes; 2d, to do away with the necessity for any technical knowledge or skill, and to reduce to a minimum the amount of ordinary care and attention, necessary to keep the outfit in good operative condition; 3d, to reduce to a minimum the time required for each analysis and to increase as much as possible the total number of analyses obtainable per hour; 4th. to increase the accuracy of the apparatus by eliminating all errors due to variations of the temperature, of chemical composition of the reagent, or of barometrical pressure; also all errors due to frictional resistance in the recording mechanism;

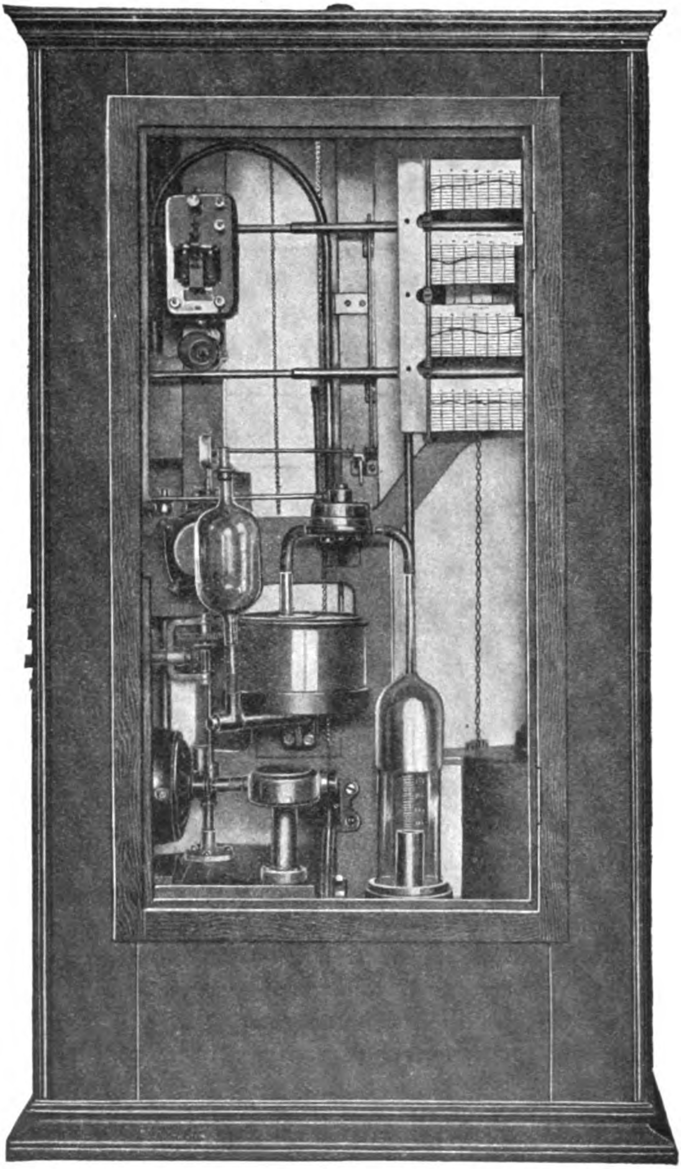


Fig. 3

5th, to make the same apparatus give CO_2 records for several boilers, thereby reducing the cost of equipment per boiler.

Fig. 3 shows this CO_2 recorder arranged to give CO_2 records for a battery of four boilers. Fig. 4 is a theoretical diagram of the apparatus.

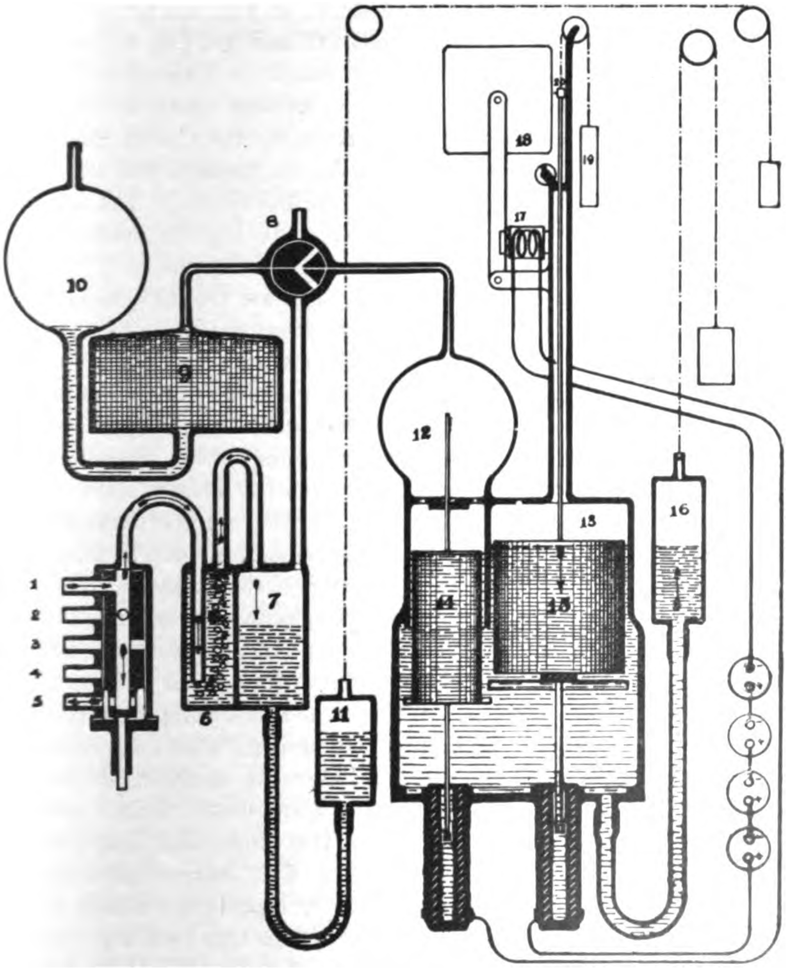


FIG. 4

Each complete analysis of a sample of gas comprises, in this case, a succession of steps or a cycle of operations very similar to those described in connection with the Orsat apparatus. All the manipulations are made automatically, the work incidental thereto being done by a small constant-speed electric motor partly visible at the lower left hand portion in Fig. 3. This motor drives, through suitable speed-reducing gearing, the mechanism by which all necessary movements of valves, liquids, recording devices, etc., are effected and controlled, in systematic manner.

The function of the movable vessel *E*, in Fig. 2, is performed, in this case, by two movable vessels (11 and 16, Fig. 4), which are counterweighted and which are raised or lowered or held stationary at certain positions and at certain times, by means of ingenious cam-actuated devices driven by the electric motor. One of the movable vessels, 11, serves to displace the sample of gas when it is first received from the boiler-flue. The other movable vessel, 16, serves to displace it during the operations of measuring, "treating", and remeasuring the gas.

In a case such as indicated in Fig. 4, where the CO_2 recorder serves four boilers, a pipe must be run from the flue of each of these four boilers to the "selector" shown in Fig. 4, at the left side. This selector is provided with a small steam injector and with four valves so operated that only one is open at a time. In Fig. 4, the valve of the "sampling" pipe from boiler No. 1 is shown open, the other valves being closed. The injector causes a stream of gas to be drawn from the particular sampling pipe which happens to be in connection with it, and to flow through the selector and out through the exhaust pipe 5. This insures a rapid motion of the flue-gas in the sampling pipe and, therefore, enables a "sample" of flue gas to be drawn directly from the boiler flue at the very time when it is to be used. The opening of the valve of each sampling pipe is so "timed" by the motor-driven mechanism, that it occurs some seconds before the sample is taken for analysis, thereby allowing the sampling pipe to be first cleared of "stale" samples. This feature overcomes one of the objections which has been found hitherto, namely, that the CO_2 records are sometimes several minutes "behind time", especially when the sampling pipe is of considerable length. In this case the sample is taken into the recorder, through the receiving vessel, 7. Before the sampling pipe is "cleared", the movable vessel 11 is raised to its highest position by the action of the cam, thus causing the liquid to fill the vessel 7 and empty it of all gas. When a new sample is to be taken, the vessel 11 descends, causing the liquid in vessel 7 to lower, and consequently, causing a certain volume of gas to be "aspirated" from the selector into vessel 7. This gas is prevented from leaving the vessel 7 by the sealing action of the liquid in the pipe connecting with the selector.

When the vessel 11 has reached its lowest position, it remains stationary, during an interval of time sufficient to allow the valve 8 to be opened by the motor-driven mechanism, and to make connection between the vessel 7 and the measuring vessel 12. The vessel 11 is then caused to rise by the action of the motor-driven cam; the liquid rises in vessel 7 and forces the gas into the measuring vessel 12. The capacity of vessel 7 being from four to six times greater than that of vessel 12, there will be more gas than is necessary for one analysis. The pressure produced by the rising of receiver 11, and the rising of the water level in vessel 7, tend to force the liquid into measuring vessel 12. This pressure would, obviously, compress the gas, were it not that room is made for the gas by the lowering of vessel 16 (which then occurs by the action of the motor-driven cam), and the consequent lowering of the liquid in space 14, until the liquid is about half an inch below the mouth of the measuring vessel 12. Consequently, the surplus gas can escape freely through the vessel 15 and through the vent pipe to the atmosphere or to an exhaust pipe. The vessel 16 remains stationary at its lowest position for a brief interval, during which the valve 8 is moved so as to close the connection between 12 and 7 and open the connection between 12 and 9. The displacement vessel 16 then begins to rise. The consequent rise of the liquid and of the " float " 14, in measuring vessel 12, causes the gas therein to be imprisoned or sealed. The further rise of the displacing vessel 16 and the further rise of the liquid at 14 now cause the liquid to rise in the measuring vessel 12, and the gas to be displaced out of the said measuring vessel, through the valve 8 into the caustic potash vessel or " treating " chamber 9. The liquid in vessel 9 is displaced to make room for the gas, the excess of liquid being forced into the supplemental receiver 10. The chamber 9, being of relatively large diameter and filled with iron-wire netting, presents, as the level of the liquid in it is lowered, a very finely subdivided chemical surface which is wet with the chemical reagent (caustic soda or caustic potash). The amount of surface exposed is approximately 40 times greater than the area of cross-section of the vessel 9; consequently, the rapidity of the absorption of the CO_2 is greatly increased. The presence of this iron netting has the further advantage of stirring and mixing up the solution when it rises again in the vessel 9, which happens when the vessel 16, after having reached the upper end of its " excursion " and having remained there a certain length of time, now descends, allowing the level of the liquid to fall in vessel 14, thereby reducing the pressure exerted on the gas in the vessel 9, causing the unabsorbed gas or " residue " to return from the vessel 9, through the vessel 8, into the measuring vessel 12. This return process is assisted by the simultaneous fall of the level of liquid in the compensating vessel 10, and its rise in vessel 9. It will thus be seen that the residual gas is measured in the same vessel in which the sample was measured before the analysis.

The final step is the estimation of this residual volume of gas as a percentage of the original volume of the sample. This is accomplished in an ingenious manner. There are two cylindrical pivoted floats, 14 and 15, in the vessel 15. Each float carries, at its lower part, an annular electrical contact which forms part of an electric circuit, indicated on the diagram (Fig. 4). Although these floats may revolve on their pivots, as they rise or fall with the liquid, an electric contact will be made by their annular portions whenever these are allowed to touch. The annular contacts are faced with platinum. The " liquid " in which they are placed is " oil ". The current which passes when the circuit is completed is only a small fraction of an ampere. Therefore, the chances of " failure to connect " are very remote. The contacts are, however, readily accessible, in case of necessity. The electric circuit is controlled at another point by a contact-segment mounted on a revolving disc which is operated by the motor-driven mechanism. The electrical contact at this segment is so " timed " by the mechanism, that it occurs only during the final period of analysis, when the percentage of CO_2 is to be determined and recorded.

When, during this period, the vessel 16 is lowered, causing the residual gas to be returned from the vessel 9 into the vessel 12, for the estimation of its volume, the floats 14 and 15 each tend to follow the levels of the liquids in the respective portions of vessel 15. The float 14 will remain stationary when the residual gas has all been returned from the absorption chamber 9 to the measuring vessel 12. If the original gas contained CO_2, the residual gas will obviously be of smaller volume; consequently, the level will not fall as low as the mouth of the measuring vessel and the float 14, which forms a sort of plunger or piston in the lower part of vessel 12, will remain at a higher position.

When, now, by the continued lowering of the receiving vessel 16. the float 15, in following the level of the liquid, has come down to a point where its annular contact touches the annular contact of float 14 the electric circuit will be closed, the electromagnet 17 will be energized, and the measurement will be recorded on the paper strip 18. It will be seen that when the circuit is closed, both of the floats 14 and 15 are in stable equilibrium because the gases in vessel 12 and in vessel 15 are thus at atmospheric pressure; and the possibility of variations in consequence of errors due to barometric conditions is eliminated.

The recording mechanism, being attached to a stem, rising from float 15, moves therewith. The recording point 21 does not, however, come in contact with the paper strip until the electric circuit is closed in the manner just described. In this manner, the possibility of errors due to the friction of the recording mechanism, and the consequent liability to failure of the float 15 to follow the level of the liquid, is obviated. The weight of the float and of the recording mechanism attached thereto can be accurately counterbalanced by a counter-weight 19. The float 15 can obviously be made to rise or fall to some extent in the liquid, when in a position of equilibrium, by varying the counterweight 19. Advantage is taken of this fact, in making the initial adjustment of the float 15, so as to insure the closing of the circuit at the exact point when the levels of the liquids in vessels 12 and 15 are the same.

In practice, when the same recording apparatus is used for several boilers, the recording point and the recording strips are duplicated. Fig. 3 shows a recording apparatus capable of giving four distinct recording charts, corresponding to four different boilers. In such a case, the float 15 carries and moves four recording points instead of one. The conditions are such, however, that only one of these points can make a record at any one time. In such a case, the driving mechanism of the apparatus automatically makes an analysis for each of the four boilers in succession and makes a record of the analysis on a chart corresponding to that boiler. This is done by a train of gears so arranged that, at the end of each analysis, the " selector " is connected to the sampling pipe of a different boiler. The connections are changed successively, in such a manner, that each sampling pipe in turn becomes connected with the steam jet and with the receiving vessel 7. At the same time, the electric circuit-connections with the recording magnets are changed in such a manner that the magnet of the recording apparatus corresponding to that boiler is alone in circuit. The proper coördination of all the moving devices, including the displacement of the vessels 11 and 16, the change of the valve, the change of the electrical connections, etc., is insured as already stated, by means of positive gearing-mechanism, all driven by the same source of motive power, consisting of a small constant-speed motor, shown in the lower left hand portion of the case, in Fig. 3. In this way, it is practically impossible for any of the different operations which have been described to take place out of their proper turn, or to be " out of phase."

One of the important sources of errors of previous forms of CO_2 recording apparatus was due to the fact that the residual gas was left in the measuring chamber 12 and had to be forced out by a new sample. In this case, at the end of an analysis, the residual gas is positively forced out and the measuring chamber is, so to speak, "cleaned" by the rising of the liquid until it fills, entirely, the measuring chamber. This is done by a preliminary upward "excursion" of the displacing vessel 16 which rises for that specific purpose until the level of the liquid in vessel 12 reaches the top. The only gas that is not displaced is that in the small tube connecting with valve 8. The succeeding analysis begins by the transfer of a new sample into vessel 7, while the residue is being expelled from vessel 12. In this way, a certain amount of time is gained in getting ready for the succeeding test. The design of the treating chamber 9 is such as to reduce to a minimum the time required for the absorption of the CO_2. The recorder can make a complete analysis and record the same inside of one and one-half minutes. Therefore, a recorder serving four boilers can give a record for each of the four boilers once every six minutes or ten times per hour. If the recorder is serving only two boilers, it will give a record for each every three minutes or twenty times per hour.

It is an important advantage of this CO_2 recorder that the measurement of the gas residue does not take place in the treating vessel 9, as it does, practically, in some forms of CO_2 recorder. The present CO_2 recorder, by adhering to the Orsat principle, in this respect, and forcing back the gas residue to the measuring vessel 12 before measuring it, avoids some more or less important causes of error due to changes in the volume of the reagent solution, by reason of changes of temperature and of actual increase due to the absorption of CO_2. In such a case, the error due to a change of temperature will, obviously, be all the more important when the total quantity of solution is large. The expansion of the liquid in vessel 9, either from absorption of CO_2 or from rise of temperature, has no influence on the final result. The vessel 10 with which the vessel 9 is connected, is open to the atmosphere and, consequently, allows adjustment to be made automatically between the two vessels, for change of volume.

The external features which distinguish this recorder from all previous forms, is the liberal use which has been made of *metal* to the exclusion of *glass* in its construction. It can be said, indeed, that glass has been eliminated everywhere except where it is desirable or necessary in order to allow the operation to be *seen* at any point or at any stage.

Damper-control. Mr. Stott, himself, is authority for the statement that the efficiency of a boiler plant can be materially improved by "watching the CO_2 records". The tests made by him, and by many others since, have shown conclusively, that the CO_2 record gives accurate information regarding the efficiency of a steam boiler. For a boiler working constantly at the highest possible theoretical efficiency, the CO_2 record would be a straight line, corresponding to a little over 20% of CO_2. In practice, such high CO_2 values are seldom attained, even momentarily. Occasionally, the records may "make a jump" to 16, 17, or even 18%; but even those results are infrequent and of very short duration, and may be considered abnormal, since they correspond to conditions of combustion which cannot be maintained for any great length of time without affecting the output, or steam-capacity, of the boiler.

The above-mentioned CO_2 record corresponds to the condition of perfect combustion, in which only the quantity of air theoretically necessary for perfect combustion, is admitted into the furnace. We all know that this ideal or theoretical condition could not be satisfied in practice. There always is, and, indeed, there must always be, a certain excess of air, as there are always some parts of the fire which have a deficiency of air even when there is an excess of air in the rest of the fire. The consequence is, that, practically, the highest efficiency attainable corresponds to a CO_2 record which is seldom higher than 15%, and is usually considerably lower, being as low as 9, or even 8 per cent., in some cases. This highest attainable line depends upon the design of the boiler plant, and, especially, upon the kind and quality of coal and the way in which it is burnt. For the very lowest grades of " culm ", the line of highest attainable practical efficiency probably could not be higher than 8%.

The desideratum, in any boiler plant, then, is a CO_2 record which is as nearly as possible a straight line, representing an average value of CO_2 which is as high as is consistent and possible, with the particular conditions of design and operation, for that plant. That line is the line of highest attainable efficiency for that plant; and there is a similar line for every plant. The examination of CO_2 records obtained even in those boiler plants which may be considered " well regulated " to the highest degree, indicates that the CO_2 " curve " is far from being a straight line; but shows " lapses from grace " or losses of efficiency which occur in somewhat erratic, unexpected, and oftentimes apparently unaccountable manner.

Now, what Mr. Stott means by " watching the CO_2 records ", is, that the careful study of such " lapses " of the CO_2 records from the line of highest practical efficiency for that particular plant, will, in nearly all if not all cases, lead to the discovery of the reasons for them; and these reasons are almost always related to the method of firing and the damper-control. The CO_2 record, obviously, renders a great service by calling .attention to discrepancies or irregularities in the method of firing or to improper methods of damper-control. When the fault is discovered and remedied, the CO_2 records bear testimony to that fact by showing a decided improvement, because the co_2 curve does not then have so many and such large breaks or notches in it.

One of the important lessons which the CO_2 recorder has taught the boiler-room expert, is that the damper must be adjusted much more *often*, and usually much *less at a time*, than it has been hitherto, if we expect to get very near the maximum efficiency obtainable in any particular plant. In the case of boiler-plants which are operated at more or less constant load, and with automatic stokers, the damper-adjustment may not need to be so frequently changed; but, in the case of boilers which are hand-fired and which supply steam for variable loads, it sometimes seems, judging from the CO_2 records, as if the damper-adjustment ought to be changed every few moments. Even in the most favorable cases, however, it ought really be changed much more often than it is.

If we admit the necessity and desirability of frequent changes of damper-adjustment, the question of finding ways and means of doing it properly and cheaply assumes some importance. In several cases the problem has been partly solved, and with satisfactory results, by making the fireman himself watch the CO_2 records, and adjust and readjust the dampers accordingly. In some cases, in large boiler plants, it might even be profitable, to have a special attendant for the purpose of watching the CO_2 records and of adjusting and readjusting the dampers. The ideal solution of this problem is, obviously, automatic damper-control.

It being evident that automatic damper-control could render valuable service, by increasing the fuel-efficiency, in a large number of steam plants, work has been done on this problem systematically, in the last year. While it seemed simple enough to let the CO_2 recorder close an electric circuit, which would start a motor that moved the damper, yet, the solution did not prove to be quite so simple as that. The truth is, that, in this case, as in the cases of all automatic apparatus, the apparatus must be so organized that it can, if not entirely replace, at least assist, human intelligence instead of counteracting its result. There being limitations to the capabilities of automatic apparatus, as there are to the limitations of the human intelligence that is at hand in the boiler room, it is necessary to exercise great foresight and to make provision, in the automatic device, for all contingencies, even that of bringing human intelligence to the " rescue ", when circumstances arise which cannot be successfully dealt with by a machine, but which require more or less prompt application and exercise of human intelligence. It is needless to say that these circumstances are of frequent occurrence in the furnace of the steam boiler, and it is obvious that an automatic device which failed to do the right thing, or which did the wrong thing, at a critical moment, would be very inadvisable, to say the least. It should be so organized that it will not, at least, put the boiler out of commission, or prevent it from doing its work, even temporarily.

The practical results which have already been obtained are satisfactory and encouraging. A detailed reference cannot be made here, at the present time, for obvious reasons. It is hoped and expected, however, that full publicity can be given to the method and the results obtainable by it, within the next few months.

Discussion on "Single-phase versus Three-phase Generation for Single-phase Railways", at Niagara Falls, N. Y., June 27, 1907.

(*Subject to final revision for the Transactions.*)

P. M. Lincoln: I agree with the author of this paper, that it is highly desirable to keep power service and street railway service separate if it is at all possible. However, at times commercial considerations may make it essential to supply both polyphase power service and single-phase railway service from the same generating station. When that is necessary, the author of this paper has pointed out several methods by which it may be accomplished. There is one modification, however, which he has not mentioned, but which I believe has considerable advantage over any of the methods mentioned by the author.

The ordinary three-phase system may be represented by an equilateral triangle, in which the three sides of the triangle will be the voltages generated by each of the three phases, as in (*a*). When we put a single-phase load on one of these legs, this triangle becomes distorted, affecting both the relative lengths and phase relations of the three phases. It assumes a form something like (*b*), Fig. 1, so that the three-phase triangle is considerably distorted from its original shape. When it is necessary to supply both single-phase and three-phase from the same generating system, we can give the three-phase voltage an initial distortion so that a true three-phase relation shall lie somewhere between the initial distortion selected and final distortion which may be expected due to the single-phase load. By this means the maximum unbalancing that can take place in the three-phase circuit is approximately one-half what it would be if we started with a balanced three-phase. Fig. 1, (*c*) shows roughly in diagram the condition that might be expected. At best the effect on the three-phase circuit is anything but good.

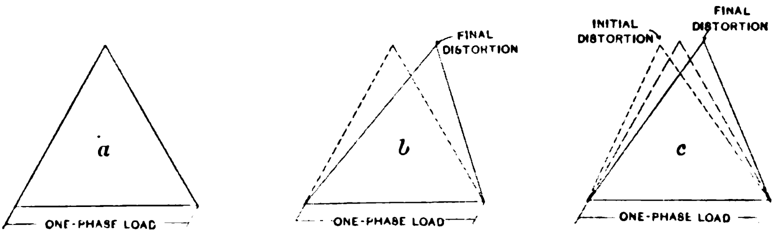


Fig. 1

Therefore, I do not feel like recommending any method or any system where a single-phase railway and a general power distribution are drawn from the same generating system; but, as I

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have already said, commercial considerations sometimes make it necessary to consider such a system.

Henry G. Stott: One other method, not mentioned in the author's paper, might be brought up for discussion; that is, the method of using the grounded neutral on the three-phase system. Where power is required for general purposes, as well as for single-phase railroad work, this method might be applicable; as, by the use of partly loaded induction motors in different parts of the line, the balance of the phases, and also of the voltages, would be restored. This makes an extremely simple combination where general three-phase power, as well as single-phase operation, is required.

Mr. V. Karapetoff: It seems to me that where difficulties should arise, on account of unbalancing, in cases where single-phase and three-phase lines are fed from the same generators, we would have to regulate the three-phase system by means of induction regulators. It is not necessary to regulate the three legs; only one phase needs to be regulated. The triangle of voltages is originally an equilateral triangle; then it becomes a distorted triangle. It is plain that this latter triangle can be made again an equilateral triangle by moving in a certain direction *one* of the phases, by having in the three-phase system a suitable induction regulator in one leg, so arranged that a vector of any desired direction or magnitude can be added to the line voltage. Therefore, the problem of regulation is not as difficult as it might seem at the first glance.

John B. Taylor: I fail to see how a single-phase induction regulator can be practically applied to a three-phase system in such a way as to compensate for the unbalancing effects of a single-phase load. More important than the drop in voltage due to line resistance, etc., is the distortion due to the reaction in the generator under single-phase load conditions.

All things considered, there will be many cases where the expense of the motor-generator set will be justified. This enables the transmission system to work on balanced three-phase load, at unity power-factor, and also removes the grounds from the transmission system. Where the single-phase load is taken as a part of a large system, unless transformers or motor-generators are introduced, a ground on the single-phase system involves, of course, a ground on the entire system and this in many cases would be decidedly objectionable.

William McClellan: The paper has reference to large systems giving opportunity for sectionalized distribution. So far, single-phase electrification has been over short distances with not more than two sections to be fed. Such a system presents little difficulty where a company is generating its own power. While from a technical standpoint the unbalancing may be inconvenient, it does not affect the coal-pile seriously. When, however, power is bought from a power company and taken from three-phase transmission lines, the effect is more serious. Under modern contracts for power, unbalancing, over a certain maximum amount, must be paid for. Under such conditions it is possible to connect the transformers in V which, however, would never give a balanced three-phase load. A better method is to connect the transformers in T and use the 90° phases on the two sections of the trolley. When these two sections are equally loaded, the three-phase load will be balanced and the average balancing of the load will be considerably better. Such a system requires, however, that the three legs at the high-tension side of the transformers be opened nearly simultaneously.

Chas. P. Steinmetz: The problem of taking care of single-phase loads on three-phase systems is rather complicated. I do not believe any induction regulator can take care of it to the extent of balancing the load. The cause of the unbalancing on single-phase load is to be found in the flow of power which with single-phase load is not constant, as it is with the balanced three-phase system, but pulsating. This pulsating flow of power gives a pulsating armature reaction; superimposed upon the fundamental sine wave of the generator it produces the effect of a double frequency pulsation or magnetism due to the pulsation of the flow of power. This results in the production of a strong third harmonic. In some conditions, in extreme cases, where the single-phase load.is short-circuited, this triple harmonic may reach disastrous values, 250 per cent. of the normal voltage, or even more. This is merely the extreme case of unbalancing.

To restore the equilateral triangle by giving it an initial distortion is open to the objection that the distortion of the triangle is not always the same but depends on the nature and the power-factor of the load. If the power-factor of the load is approximately constant, within a moderate range, as with single-phase railroading, this can be done. But, after all, with any generator of reasonably good regulation, the matter usually is not serious because an induction motor can take care of a very great distortion of the equilateral triangle and still work with no appreciable change in efficiency, no appreciable change of heating; in most cases then we can let the triangle become as distorted as it chooses, and the induction motors and other apparatus will show no difference, except perhaps synchronous converters. Synchronous converters in such systems would necessarily be installed, as they usually are in railway work, with heavy reactances, reactances of ten per cent. or more in the leads. This reactance, by phase displacement of lead or lag, can take care, not only of line drop, and control of voltage, but also of distortion of the triangle, and thus supply at the converter the equilateral triangle with a greatly distorted generator triangle, by merely a small change in the angle of lag of the three different phases, one of the three-currents lagging perhaps, while the other is leading to a small extent. So the converter can also take care of itself.

The main difficulty is where lighting is done from several phases. But even there if we look at the distortion of the triangle, with single-phase load, we find that naturally the loaded phase drops with the ordinary single-phase load. Of the other two phases, one drops more than the loaded phase, and the other remains practically constant; that is, of the two unloaded phases the distortion is such as to keep one of the phases almost constant and in that phase through a potential regulator which has relatively little work to do, constant potential may be supplied. That is probably the simplest way of taking care of unbalanced loads. My old scheme, the monocyclic system, was to build the generator three-phase; use one phase for lighting and maintain it as constant voltage, and carry the three-phase load by the auxiliary phases. After all, that was another form of Mr. Lincoln's proposition to start with a distorted three-phase system and use the distortion to distribute the load between the different circuits in the desired manner.

A. H. Armstrong: I am inclined to look at this matter a little more broadly than some of the previous speakers. For instance, the method proposed by Mr. Lincoln can be used successfully in cases where the railway company generates its own power, although in such cases the company would have the privilege of generating and distributing single-phase power, and the simplicity of single-phase distribution would recommend it above all others. We are confronted, however, with the problem of power purchased from foreign concerns, and the tendency of the times seems to be toward establishing large centers of power distribution. The generation and distribution of power is carried on as a separate business by itself. It may be associated with lighting, railway, and power industries, but in any case it is generated and distributed three phase. It is a very difficult problem to connect single-phase railway systems to a three-phase power distribution system without interfering in some degree with other uses of a common power supply. In fact, managers of power distribution systems are very loathe to make contracts which involve the use of single-phase power for railway purposes. In such cases the introduction of a motor-generator set seems almost necessary, aside from the question of frequency supply, if the distribution circuit of the power producers is to be properly safeguarded.

Unfortunately, in a large number of single-phase projects suggested, the margin of profit between installing alternating-current apparatus and direct-current apparatus is rather small. Owing to the inferiority of the alternating current railway motor, there is no advantage in adopting alternating-current car equipments unless there is a considerable reduction either in first cost or operating expense, or both. The added expense of motor-generator sets oftentimes acts as a serious handicap when considering the installation of alternating current railway equipments fed from a foreign three-phase source of supply. In such cases it will be necessary to use some of the methods proposed for balancing the load on the three phases rather than consider the expense of a motor-generator set.

DISCUSSION ON "THE CHOICE OF FREQUENCY FOR SINGLE-PHASE, ALTERNATING-CURRENT RAILWAY MOTORS", AND "TWENTY-FIVE VERSUS FIFTEEN CYCLES FOR HEAVY RAILWAYS", AT NIAGARA FALLS, N. Y., JUNE 27, 1907.

(Subject to final revision for the Transactions.)

Mr. H. G. Reist: With engine-driven generators the problem is a comparatively simple one, since not much difficulty is experienced in building machines for 15 cycles. The cost of the generators will be increased somewhat, perhaps 30 per cent. With turbine-driven generators the increased difficulty is very much more serious. As has been pointed out by one of the speakers, in smaller size generators, about 2000 kw., capacity, the increase of steam consumption on account of the limit in speed becomes serious, and undoubtedly there will be many places where generators of that size, or smaller, will be needed for long distance railway work. On larger sizes, the speed is more favorable for the turbine, but the generators have to be built with two poles only, which makes it a difficult designing problem. The machine becomes massive, the magnetic circuits become exceedingly long, and the weight of the machine must be greatly increased over that of the 25-cycle machine. Roughly, probably the weight and the cost would be increased fifty per cent. over a similar 25-cycle machine. The efficiency would also be a little less, although that is probably not a very serious matter; it might be a per cent. less at full load than with the higher frequencies.

C. W. Stone: If the design of turbine-driven generators is to be complicated by a combination of lower frequencies and single-phase operation, the generator becomes almost prohibitive unless 450 revolutions instead of 900 are used on the large capacity machines. On machines of 8,000 or 10,000 kw. capacity, 450 revolutions is very bad from the steam end. All the recent 25-cycle machines of large capacity have been run at approximately 750 revolutions. To increase the speed from 750 to 900 rev. per min. and make the generator both single-phase and 15 cycle is not to be considered.

E. J. Berg: While I do not believe that it will be necessary to resort to a frequency lower than 25 cycles, I think that some of the objections raised against the lower frequency are not well taken. A so-called half-frequency generator was invented several years ago, a generator with a given number of poles giving half the frequency of the regular generator operated at the same rotative speed. In construction, this generator was similar to the induction motor; in its action, to the well-known frequency-changer. Instead of exciting the field by direct current, alternating current of a given frequency was used, and the magnetic field made to rotate in the same direction as the armature but at half its speed. By this scheme, the frequency corresponding to one-half the speed could be obtained, not only from the stationary, but from the revolving member. Obviously, the exciting current had to be delivered at the lower frequency, but this was not objectionable, as the actual power supplied was slight and therefore the inefficiency of the low-speed turbine of little consequence.

L. B. Stillwell: I am much pleased to find a question of such transcendent importance as this, of the best frequency for railway work, receiving the serious consideration of the engineers of our manufacturing companies.

The electric railway fraternity now for the first time is undertaking the electrification of railways operating heavy traffic and employing steam locomotives. This work presents a problem more important commercially than any we have hitherto attacked. We are dealing with people who are not of the type that we had to deal with in the early days of electric lighting. The railways of the United States are managed by men whose education in most instances is largely an engineering education. They have their own excellently prepared and thoroughly experienced engineering staffs who will pass upon these questions. Therefore, it is of especial importance in considering such questions as this, that we should take a broad view, saving money for our clients by fighting out differences of opinion on paper and on the floors of these conventions, and if possible, agreeing among ourselves upon all necessary fundamental standards.

The paper which Mr. Putnam and I had the honor to present before the Institute in January last raised this question of frequency in railway service. Our feeling was that a mistake in all probability was being made. The figures which we worked out were intentionally broad, probably broader in application than any we shall see in our time, but it seemed advisable to look at the entire railway field and attempt to realize the magnitude of this problem. We therefore followed out our analysis of the comparative costs of operation, by figures showing the total cost of electrifying the railways of the United States. Some of the technical journals, whose specialty is steam railway practice, have ridiculed the idea of considering even the possibility of the electrification of all the steam railways in the United States. Probably no one here expects that this will be done in the near future, if ever; but it is significant to find that if we consider the average railway in the United States upon which there are but seven trains in each direction per day, and applied to its operation single-phase alternating current, using a transmission voltage equal to that which is to-day in use transmitting power from Niagara Falls to Rochester and Syracuse, it would be possible to save approximately 18% of the present operating costs. This conclusion has not been assailed in respect to anything that is material. Even if we admit every exception to our total figures which was noted in the discussion, we still have a saving of at least 15%. This is a very important and a surprising fact. It indicates not that all of the railways in the United States will be electrified in the next ten years, but it does indicate strong probability of a more rapid extension of the application of electricity to the operation of trunk-line systems than has been generally realized, even by electrical engineers.

In calculating the reduction in operating costs, it is hardly necessary to say that we recognize also what several of our critics have kindly pointed out; namely, that the principal object in view when the management of a railway decides to electrify its lines is not reduction of operating expenses but increase of earning power. This fact is well known and has been referred to in many previous papers and discussions. The two reasons undoubtedly constitute an argument operating powerfully to induce railway electrification. The point which I wish to emphasize is that this electrification is in all probability coming at a rate which greatly emphasizes the importance of early standardization of everything essential to interchange of traffic.

A recent bulletin of the Census Bureau of the United States, prepared by Mr. Martin, shows that from 1900 to 1905 the products of companies manufacturing electric apparatus were more than doubled. In the year 1900 few would have dared to predict such an increase.

When we take the broad view and realize the probability of a more rapid extension of the use of electric equipment in trunk-line railway service, the suggestion that it is of utmost importance to adopt a standard frequency especially adapted to this work appears less radical than it does to the factory engineer who is interested, primarily, in the problem of designing a complete line of turbo-generators.

The total cost of electrifying a railway, is in general, not less than $200 per kilowatt of generating capacity installed, and in considering the effect of 25 versus 15 cycles the difference in the cost of the average turbo-generator might easily be $5 one way or the other without materially affecting our conclusion. Moreover, in dealing with the problem of trunk-line electrification we may as well throw aside all of the smaller generators, as this service will rarely, if ever, call for a generating unit of less than 3000 kw. A single freight train, such as is hauled over some of our trunk lines, would require one 3000-kw. generator.

There is another field the limits of which, while not clearly defined, are sufficiently understood; that is, the interurban. Much argument has been presented at various meetings of the Institute this year bearing upon the question of the possible use of a 1200-volt direct-current system as a substitute for the high potential alternating-current system. This system, perhaps, has its field in the interurban service. I think it can have no proper application in the broad service of trunk-line railways of which I am speaking. A potential of 1200 volts on the trolley or third-rail will never be satisfactory for the operation of freight trains. We must go radically higher. Anything less than 6000 volts in single-phase service is out of the question, and the question for us to decide is: " What frequency shall be adopted for alternating-current railway operation "?

The paper which Mr. Storer has read is one of the exceptionally valuable papers of the year. It contains precisely the kind of information which is needed in dealing with the very important question of frequency; and a half dozen pages of facts, such as he has given us, are worth any number of pages of general speculative opinion. In the discussion of my paper in January, the engineers of both the great manufacturing companies engaged in single-phase work, who had to do with the design of the motors and their application to trucks within the limits of space available, testified unanimously to the effect that at given cost 15 cycles secures one-third more draw-bar pull than does a frequency of 25 cycles. The people who will buy electrical apparatus to equip trunk-line railways will buy draw-bar pull. Recognizing this, it seems to me that we must recognize also the fact that in view of the evidence set forth in the Institute papers and discussions this year, 15 cycles should be adopted in general for heavy railway work. I do not mean to say that a resolution to this effect should be passed, but I do say that unless evidence in favor of 25 cycles not hitherto presented can be brought forward, 15 cycles should be chosen by consensus of sound engineering opinion and should be introduced into practice as promptly as possible.

At the meeting in May when Mr. Sprague's paper was read some interesting facts were brought out in the discussion, especially the statement that one of the great manufacturing companies since January had produced a new single-phase motor of remarkable characteristics which operated substantially as well at 25 cycles as at 15 cycles. This is a very interesting statement and it suggests information which I hope will be promptly and conclusively disclosed because some of us in the consulting field are now confronted by the problem of frequency for railways which at the present time are considering only the equipment of a terminal or a short division, but which by reason of the saving effected in operation and of increased earning power are morally certain to extend that electrification over much greater parts of their existing systems.

W. N. Smith: I cannot escape the conclusion that the question of electrification of steam railroads is so extremely broad that, as has been indicated by both Mr. Storer and Mr. Stillwell, we should not deliberately tie ourselves down to any existing commercial frequency which was developed primarily for lighting and stationary power.

If the steam railroads want draw-bar pull, which is unquestionably what they need to get the maximum amount of tonnage over a given track in a given time, they will not wish to be handicapped by the facilities offered by some local power company, no matter how large it may be, which may have 25 cycles to offer, if 15 cycles is going to be the best thing for them to use. Great as is the power development here at Niagara Falls, I doubt if there would be enough 25-cycle power generated to supply the commercial demands of this region, now developing so rapidly, and at the same time supply the railway power required by such wholesale electrification as it is conceivable that large railway systems might eventually undertake. I do not believe that there is sufficient power capacity at present installed in any one plant anywhere in the country which would justify the undertaking of the wholesale electrification of a large steam railroad in its own vicinity, in addition to its own commercial load. It appears to me that the problem will without doubt result in the railway companies either having their own power stations, and getting developed for themselves the kind of machinery that they need the most, or calling into existence commercial power companies which will do it for them, developing coal mine power or large water power in such units and by such methods of distribution as the railway companies, their biggest customers, may demand.

William McClellan: If we examine these papers carefully, we shall find a decided agreement between the two authors as to facts, though the opinions and conclusions given are somewhat different. Apparently there is no uncertainty as to the weight-efficiency. Variable adhesion is eliminated as having no practical bearing. As far as the difficulty of generating 15-cycle power by turbines is concerned, Mr. Berg has anticipated me. We had a paper a year or two ago on a type of generator excited with alternating current. It was suggested that such a machine could be built self-exciting, in our case for 15 cycles, and run at double speed, thus making it possible to drive it efficiently by a turbine.

Apparently, the chief argument against 15 cycles is the difficulty of changing present commercial standards; this is certainly entitled to most serious consideration. Nevertheless it should not be forgotten that great advances have been made in the past by discarding what seemed at the time as fixed practice. This was one of the arguments against the adoption of the metric system. Notwithstanding this, it was announced a few days ago that the Baldwin Locomotive Works had built a locomotive with its regular workmen and had used the metric system throughout. The engineers and workmen were well pleased with the system and the arguments against its adoption were apparently refuted.

It has also been stated that a low frequency would not be suitable for other purposes than motive power. In this connection it should not be forgotten that it is probable that large lighting and power loads will not be worked from the same bus-bars as fraction loads. It is also worth noting that the present tendency of economic progress is to limit transportation companies strictly to the transportation business, and it is not likely that they will go into the business of selling power. Lighting and power for their own shops, stations etc. is relatively unimportant.

The important point noted in the Stillwell-Putnam paper was that the cost of the motive power equipment is by far the greater part of the expense of electrification. This brings us directly to the motor and its efficiency.

A short time ago there seemed to be a decided unanimity of opinion that the compensated-field single-phase motor was the type which the manufacturers had found to be most advantageous. It was expected that it would be greatly improved but the type would remain standard. With this motor, much would be gained by using 15 cycles. The engineer with the facts before him, and if not limited by local considerations, would necessarily hesitate a long time before refusing to adopt this motor.

Recently, however, we have had public notice that another type of motor is developing rapidly and is said to be nearly as good as the direct-current motor without commutating poles. From the standpoint of both weight and efficiency, this motor will perhaps not offer increased advantages when adjusted to a circuit of lower frequency than 15 cycles. If so, the whole matter is uncertain, and it would be exceedingly unwise to make any decision whatever until we have more definite information in regard to this motor.

It is worth repeating that the whole argument centers around the motor, or motor capacity, if you will, and no decision should be made to standardize frequency until the type of motor is standardized first.

Chas. P. Steinmetz: Probably the railways will generate their own power. At the same time it is a serious matter to depend on one power house only, or even two power houses, and if in an emergency power can be derived from some other station it is a great advantage.

The amount of power which would be required by the steam railways after electrification is frequently vastly overestimated. I understand some investigation on this subject has been made by Mr. Ferguson of Chicago, which I hope will be communicated later.

I believe the conclusion was that if all the railways entering Chicago received their power from Mr. Ferguson's steam-turbine station, the railway load would by no means be the largest load on the system, but probably within the overload capacity of the station.

The question before us is: first, whether the adoption of the lower frequency is necessary; secondly, whether this lower frequency should be 15 cycles or any other frequency. At present we have two standard frequencies, 25 cycles and 60 cycles, but the spectres of sundry other abandoned frequencies still haunt the electrical engineer—125 cycles, 133 cycles, 50, 40 and 30 cycles. It appears to me, and probably to everybody who remembers, and still sees the difficulties due to the existence of these odd frequencies, that it would be disastrous to introduce another frequency and then after a year or so find it was not necessary and have to abandon it. Therefore, we should be extremely careful to see whether a lower frequency is necessary. If it is necessary, which frequency should be chosen?

I do not believe 15 cycles is a suitable lower frequency. If we have to use a lower frequency it would be because the alternating-current railway motor is practically inoperative, at least in larger units, at 25 cycles. If that is the case, then 15 cycles probably is not yet the most suitable frequency; but the most suitable frequency is far lower than 15 cycles, and 15 cycles would perhaps be a compromise frequency. The experience of compromise frequencies and compromise designs has been disastrous and would better not be repeated. If it seems wise to adopt lower frequencies, we should probably have to adopt not 15 but 12.5, or even 10 cycles.

In considering lower frequencies we must realize that with the single exception of the series alternating-current motor, every part of the system, from the steam turbine generator to the incandescent lamp lighting the cars, the lower frequency is a handicap. This brings us to the need of a lower frequency. We must consider that every type of electrical apparatus has a frequency at which its design is most economical, most satisfactory, and most reliable. For small apparatus usually a somewhat higher frequency and for large apparatus a somewhat lower frequency is best suited. For instance, economically the most efficient frequency for the induction motor is 40 cycles; as a result, induction motors are built for 60 cycles or 25 cycles, both frequencies being sufficiently near the economical frequency for practical purposes. The 60-cycle frequency is mainly used with smaller motors, and 25 cycle with larger motors, and the maximum economy for smaller sizes shifts upward, and for larger sizes downward in frequency.

In the transformer we find the maximum economy is beyond the commercial frequencies. The 125-cycle transformer is better and more economical than the 60- or the 25-cycle transformer. Where the maximum economy lies we do not know; there must be some definite frequency, because we know that the alternating-current transformer is not well suited for 10,000 cycles; it is difficult to design; not economical; that is, 10,000 cycles is too high a frequency, but within the range of available frequencies, the higher the frequency the better for the transformer.

The maximum economy, of the synchronous converter is at 25 cycles. A converter designed for a frequency higher than 25 cycles, or lower than 25 cycles, is, as a rule, inferior to the 25-cycle converter.

In the alternating-current series motor the maximum economy is at the lowest possible frequency; the lower the frequency the better the motor. The best series alternating-current motor would be the motor designed for zero frequency; that is continuous current. In that I agree with Mr. Sprague. In any other apparatus, the larger the size the more urgent the need of lower frequency, and while good results have been obtained with 25 cycles on moderately small motors in interurban service; for large units, as heavy locomotives, 25 cycles seem almost impracticable for the series alternating-current motor.

It is evident then that the frequency must be lowered so as to approach that of maximum economy, or the type of the motor must be changed. There is no reason to assume that the series motor is the final development of electric railroading. I have really never felt satisfied that the series commutator motor is the solution of the problem and have repeatedly said so. There are other kinds of motors in which the maximum economy is not at the minimum frequency, but is, as near as we can judge at the present time, not far from 25 cycles. If then we adopt the lower frequency, we might find that we have handicapped ourselves in designing alternating-current commutator motors of different types.

Mr. Ernst Alexanderson has succeeded in devising a type of motor in which it appears that the maximum economy of the alternating-current commutator motor is not at zero frequency but probably is in the neighborhood of 25 cycles, and for this motor that would be the best frequency. In this respect I disagree with Mr. Armstrong in the data on the relative comparison of 25-cycle and 15-cycle motors. I believe that his statements rather represent a period which is past, but still influenced by the experience with the series motor. As far as our present experience goes, the two frequencies, 25 and 15 cycles, in railway-motor design at the present time seem to be equal in economy, and for all I know 25 cycles may be the better frequency. That necessarily means, that 15 cycles has no right to exist.

The great and only difficulty with the alternating-current motor is the commutation; all other troubles are secondary, and merely results of the limitations imposed upon the design by the attempt to make the sparking at the commutator least destructive: During the operation of the motor electromotive forces are induced in the short circuited coil under the brush, which lead to more or less disastrous sparking, and heating of the commutator, destruction of the brushes, energy losses by parasitic currents, etc. To reduce this effect we can either reduce the electromotive forces induced in the short-circuited coil, by reducing the frequency—and that is after all the gist of the desire to lower the frequency: to get lower electromotive forces induced in the short-circuited coil at commutation—or we can attempt to reduce the currents produced by these electromotive forces by inserting high resistance commutator leads. This is beneficial to some extent, although it introduces the great difficulty to protect these high resistance leads against self destruction by excessive local heating. But the benefit is limited, because while we reduce the current the insertion of resistance raises the voltage. The solution of the difficulty is to modify the type of the motor so that no electromotive forces are induced in these short-circuited coils, and that is what Mr. Alexanderson has done and concerning which I believe he will give us a paper in a very short time.

Mr. Peter Junkersfeld: Considering passenger trains only, and assuming for the sake of argument that it would be physically possible to electrify all the steam railroads centering in the city for a distance of 25 miles from the respective passenger stations, within the next year, we have estimated that the total power demanded by these various railroads would probably not exceed 20 per cent., of all the power generated in Chicago by all the various companies. This figure of 20% would even then be true only for the next year. After that the proportion of power demanded by the steam railroads would decrease, due to the fact that the amount of power required for all other purposes increases in a much faster ratio. The large amount of industrial power and the very large amount of interior lighting not yet supplied electrically and that still to be developed in Chicago would justify the opinion that at the end of five years the total steam railway demand would not exceed, possibly would be less than, ten per cent. of the total electric power generated in the city. This applies to Chicago and to the railroads for a distance of 25 miles radiating outward from their passenger terminals, so that as Dr. Steinmetz has said the proportion of power which will be demanded by the electrification of the steam railroads is not nearly so much as we might imagine.

Gano S. Dunn: How would it work out if you included the freight?

Peter Junkersfeld: We made no calculations on that, and it is a hard thing to estimate.

The most optimistic speakers on this subject of railway electrification have said that they hardly expected to see all of the railways electrified within their lifetime; in other words, it is largely a problem of the next generation. We all agree that we should look out for the next generation, but in doing so we should not neglect the present. The electrification of steam railways at and near their terminals, however, is particularly important, in fact that problem is a live and pressing one now.

In the electrification of such terminals the question of direct current or alternating current has by no means yet been settled. There is still a great deal of controversy on this point, and the probabilities are, in my mind, that ultimately the direct current will perhaps be largely used in electrifying terminals. This does not apply to the electrification of long steam railroad lines, trunk lines, etc., but it does apply to the electrification of terminals, not only because of the present state of the railway motor art, but also because of agitation against overhead high tension wires and things of that sort particularly in large cities.

We seem in this country to be passing into an era in which public regulation will perhaps have quite a great deal more effect on electrical development than in the past, and we are confirmed in that impression if we observe the experiences in other countries. In many of these the electrical development has not been so great as in this country, not because they are less ingenious, but because they have had certain handicaps. These handicaps may appear here, there is already some evidence that they will appear, and may work somewhat against the operation of terminals with high tension overhead trolleys, but may not work against future similar single-phase operation of the long railway lines.

Coming now to the question of power supply for terminals, and even admitting for the moment that possibly single-phase motors could be used for that purpose, we should be extremely careful before recommending an odd frequency, because on the crowded tracks of the terminals the question of reliability and continuity in moving the trains is of primary importance; of much greater importance than the moving of the trains between the large cities. In order to secure the best results it should not only be possible for the railway companies to buy power, when this can be done more economically but at least to be in a position to readily interchange power with other power supplying companies. Otherwise the railroad companies will have to make large investments in reserve power equipment to protect their business. The greatest factor in economical electric power generation is a diversified demand, which means a very large number of peaks, and as a result non-coincident peaks. One of the greatest factors in electrical development in a community is low cost of electric power. That can only be secured in the ultimate by having an arrangement so that the interchange of power can be made readily and quickly between the different power consuming systems whether owned or operated by one or by several companies.

The selection of the frequency for any given service should be based on the predominating demand. In a number of the larger cities in this country the predominating demand has been in favor of 25 cycles. That condition still exists to-day, and Dr. Steinmetz has told us that for rotary converters work, and which is 75 per cent. at least of the total demand in three or four of the larger cities that 25 cycles is the best frequency. For that additional reason we should be careful before recommending any odd frequency if we want to conserve the best interests of the various companies or clients we represent.

Henry G. Stott: I think that the question of supplying power for railroads has been looked at from a slightly different standpoint than it is by those who are accustomed to the conditions obtaining in most of the large companies that are developing their own power. I wonder which power plant in the United States could give an emergency supply equal to 25% of its rated capacity. Railroad plants and lighting plants have to be designed for a peak load. In a lighting plant the peak load will last not to exceed 400 hours per annum. That means an enormous investment for a short time. The railroad plants have practically a peak load of from 800 to 1000 hours per annum. How can we expect either our lighting plants or railroad plants to carry a reserve of 25% above their peaks for the purpose of guaranteeing a supply to anyone else, and if they do it, at what price can they do it?

The question seems to me to be one which will be solved by the location of a number of plants along our railroad lines. These plants will be able to give a much more reliable service, which, after all, will ultimately be the criterion applied by everyone to the question, rather than the cost. Imagine, for example, a transmission line from Niagara Falls to New York, and our railroads depending upon it, and subject to every thunder storm that comes up. I have no data at hand to show what the average interruptions of such power would be, but I know this—it would be greatly in excess of the interruptions which would obtain in a number of smaller plants distributed along the line. In other words, we can get better insurance by carrying our power in the shape of coal on freight cars than we can by carrying the power on high-tension wires. The insurance given by a number of distributed plants is going to be infinitely greater than we can obtain in any other way.

A. H. Armstrong: From the discussion it would appear that certain advantages in motor design can be taken advantage of at 15 cycles which are not possible with higher frequencies. The problem now becomes one of weighing possible advantages of motor construction against the handicap of using 15 cycles for the generating and distributing system, and, seeing if these advantages are sufficiently great to warrant the introduction of an odd frequency with all its engineering and commercial complications. The history of alternating-current distribution has been a constant tendency toward the adoption of lower frequencies as the demands of new apparatus became pressing. Up till now the question of low frequency has been governed by the performance of converters. A frequency of 25 cycles has been sufficiently low to satisfy all the needs of the situation. With the advent of the alternating-current single-phase motor, we have a type of apparatus calling for low frequency, but the greater advantages of 15 cycles must be great indeed to warrant a departure from the standard 25 cycles now in universal use, especially as the single-phase motor is not in any sense inoperative at the higher frequency. It is not a question of the adoption of 15 cycles in order to make alternating-current motor installations possible, as the recent inventions of Mr. Alexanderson and others have given us a motor which is thoroughly commercial at 25 cycles.

I agree thoroughly with Mr. Junkersfeld that the electrification of steam railroads is not to be considered entirely from an alternating-current standpoint, and instead of steam road terminals presenting a problem calling for a change in the frequency of supply in order better to accommodate the limitations of alternating-current motor design, I would suggest that this class of railroad electrification presents a problem of alternating versus direct current with a decided preference for direct current.

While recent improvements have made the alternating-current motor a thoroughly commercial piece of apparatus with a frequency supply of 25 cycles, due weight must be given to the further consideration that any continued development of this type of apparatus must show further improvements which will make 25 cycles still more desirable; in other words, having a successful 25-cycle alternating-current motor to-day, we can look to the future with the confident hope that any continued development will still further minimize any possible advantage which 15 cycles may enjoy over 25 cycles. At such a short period as two months ago, it appeared that a frequency of 15 cycles was necessary in order to make possible the construction of large alternating-current single-phase motors giving good commutation. The improvements made in two months, however, have made the adoption of 15 cycles less attractive and it is fair to assume that we have not heard the last from alternating-current motor designers that the future holds bright promise of still further developments. If we can get a motor just as good at 25 cycles, or even nearly as good, there is no reason to adopt low frequency. In fact, there is every reason to adhere to a frequency so universally in use as 25 cycles.

N. W. Storer: I have only a few words to say in conclusion. Mr. Steinmetz raised the point in regard to suitability of 15 cycles for railway work. He insists that the lower the frequency the better the motor will be. On this point I cannot agree with him. There is much more to be considered in building a single-phase motor than simply to reduce the short-circuit current to a minimum and thus obtain good commutation. If the frequency is reduced much below 15 cycles the pulsations of torque will cause considerable trouble. Everything considered, I regard 15 cycles as the best frequency for railway purposes. It is a simple matter to obtain very satisfactory commutation in a 15-cycle, single-phase motor. Within the last few days we have been testing the locomotive of which I speak and I have seen the motor carry 100 per cent. overload in current for several minutes at a time when hauling a train with the brakes set, and there was practically no sparking at the commutator, the commutation being much better than almost any of the standard direct-current series motors could do under similar circumstances.

So far as commutation is concerned, we have not regarded that as the main reason for recommending a lower frequency than 25 cycles for railway work. Our desire has been simply to increase the capacity of the motors. If this Alexanderson motor which has been mentioned by so many speakers is able to give the same capacity at 25 cycles that the compensated series-wound motor gives at 15 cycles, I should say by all means stick to 25 cycles, unless there are some other defects in the motor of which we are not aware. No one wishes to add another to the standard frequencies any less than I do. We should cling to the standards as far as possible. I believe that if in future development it is found that the installation of 15-cycle current for the electrification of a large system can be done more cheaply and operated more cheaply than the same work can be done with 25 cycles, the 15 cycles will certainly be used. As I have said before, it is solely a matter of dollars and cents.

Now, in regard to power distribution, I am much gratified to learn that the power required by the steam railroads entering Chicago is such an insignificant amount, compared with that required for other purposes. For this very reason there should be practically no interference in that case with the systems now in operation. The steam railroads certainly will require enough power when they electrify their terminals in and about Chicago, or any other large terminal, to build their own power houses and furnish their own power throughout. I do not believe it would be at all feasible for the company to draw, even to a very limited extent, from the lighting companies for power to operate their railways.

I agree with Mr. Stott that it is impossible for the various industrial plants to carry sufficient reserve capacity to take care of 25 per cent., or 20 per cent., of their normal load to provide for railway emergencies, particularly as the biggest railroad loads will come just as they do in street car service, at the hours of the day where the lighting load is heaviest and all the people want to travel at the same time. Steam railways must work out their own salvation. In electrifying their lines they must provide sufficient reserve capacity to take care of the entire system.

DISCUSSION ON "THE VECTOR DIAGRAM OF THE COMPENSATED, SINGLE-PHASE, ALTERNATING-CURRENT MOTOR", AT NIAGARA FALLS, N. Y., JUNE 28, 1907

(Subject to final revision for the Transactions.)

V. Karapetoff: In the year 1904, I contributed to the Institute TRANSACTIONS a complete performance diagram of the series single-phase motor. The diagram is similar to the well-known circle diagram of an induction motor. Assuming the permeability of iron as constant, the reactance of the motor is constant, and there results a semi-circle, as the locus of the primary current. Then by simple graphical construction it is possible to obtain input, output, speed, and efficiency. Soon after I had delivered the paper before the Pittsburg Branch of the Institute, I was fortunate enough to have in my possession complete performance curves of two single-phase motors. One was, I think, a 5-h.p motor, the other—a 25-h.p motor, both tested very carefully. In working out backwards the diagrams of these motors, by plotting the actual locus of primary current, I found that instead of being a semicircle, as it should be theoretically, it was a different curve, which for practical purposes could be assumed to be the arc of a circle, considerably flatter than the semicircle. Upon investigation, I found this was due entirely to saturation in the iron. Then I assumed empirically that for a single-phase series motor the locus of the primary current is represented by an arc of a circle, and I deduced graphically expressions for input, output, speed, etc. The saturation, and the variation of permeability which it involves, depend on the field current, and therefore can be determined from the short-circuit curve (locked saturation curve) of the motor.

I wish to call your attention to this fact, because in all the literature on the subject that I have happened to come across, the effect of saturation has not been taken into account. Diagrams of series motors derived on the supposition of a constant permeability, are good enough to demonstrate to the student the theory of the motor, but should not be used in the predetermination of actual performance.

DISCUSSION ON "COMMUTATING-POLE, DIRECT-CURRENT RAILWAY MOTORS", AT NIAGARA FALLS, N. Y., JUNE 27, 1907

(Subject to final revision for the Transactions.)

Gano Dunn: I see a tendency to hail the commutating-pole motor as the direct-current motor of the future. I heartily appreciate Mr. Anderson's paper, and the facts it brings out with which I am in substantial agreement; but I think it illustrates that we are liable to fads, and that the great success that has attended the introduction of the commutating pole so far has led some of us to attach to it too much importance. I regard the commutating-pole motor as applicable to certain classes of machines or conditions of design, such as low voltage, very large size, very high speed. These are found in direct-current turbo-generators, variable-speed motors, such as are known as field-weakening motors, railway motors where the space is crowded—in short, all machines where the commutating limit of capacity is reached before the heating limit. There still remain other classes of machines where none of these conditions applies. We have not yet exhausted our ingenuity in designing motors, so perhaps we may soon be able to equal in weight, cost, and efficiency, the commutating-pole motors, and without their complication.

It should be borne in mind that the commutating pole adds considerable complication. One of the principal advantages of direct-current motors in the past has been their simplicity, and simplicity is of first importance in electrical design.

It may be said that in a four-pole motor we need add only two commutating poles, and we may modify in one way or another the general type of the commutating-pole motor to make it more simple; but when all has been said and done, we have a motor that has several more poles and considerable additional complication in its windings and connections.

J. C. Lincoln: Have these 1200-volt motors ever been used in practice?

E. H. Anderson: I do not know that there are any 1200-volt motors in this country in railway service. There are some contracts, however, which have been taken, and motors are building for 1200 volts. These motors have been tested on testing stands as high as 1800 volts for commutation.

W. N. Smith: Does the commutator require any more room, any more air-space around it, than with the older type of motor, in order to prevent flashing-over to the frame in actual service.

E. H. Anderson: On the 600-volt motor there is usually about 1.25 in. flashing distance, and on some motors as low as 0.5 in. Dirt, copper, and carbon dust affect the flashing distance very materially. If we have a commutator which runs very much cleaner, does not have the copper and carbon dust, we do not need as much flashing distance. However, in order to improve in that direction, 1⅜ or 1½ in. creeping distances are allowed on 600-volt motors and 2 to 2½ in. on 1200 volts. The commutator does not need to be as long on 1200 volts as on 600 volts, because of less current to be carried.

DISCUSSION ON "THE ATTITUDE OF THE TECHNICAL SCHOOL TOWARD THE PROFESSION OF ELECTRICAL ENGINEERING" AND "ON THE CONCENTRIC METHOD OF TEACHING ELECTRICAL ENGINEERING", AT NIAGARA FALLS, N. Y., JUNE 27, 1907

(Subject to final revision for the Transactions.)

V. Karapetoff gave an abstract of his paper and said in conclusion: I appear with this paper before the Institute, because of my conviction that the Institute is competent, as a body, to dictate to the technical schools the requirements which their graduates ought to possess. I hope to see the day when the management of the Institute will appoint a committee on technical education. We now have thirteen committees—not a very lucky number—I wish this number could be increased to fourteen and the committee I have suggested be appointed.*

F. B. Crocker: Professor Norris says:

> Electrical engineering is taught as an application of mechanics, the only difference from other branches of mechanical engineering being in the source of the forces and the methods of transferring and transforming energy.

I object to that expression, because it is not true. Mechanical engineering is a fine profession, no one has greater respect for it than myself, but electrical engineering won its independence some years ago, and I think it is a little late to speak of electrical engineering as being a branch of mechanical engineering. Another reason why I object to it is that it leads to unpleasant feelings. Taking another step backward, we find that the civil engineer considers that every engineer who is not a military engineer is a civil engineer. I presume that Professor Norris used that expression in a general way, meaning that we are dealing with mechanical problems; but in the Engineers' Building in New York the mining engineers, mechanical engineers, and electrical engineers are certainly on terms of equality, and I cannot see any reason for subordinating one to the other. It has usually been the custom in the education of electrical engineers in this country to consider electrical engineering as part of mechanical engineering or physics. Nearly all courses of electrical engineering were grafted on, or formed parts of a course in mechanical engineering, or a course in physics. Columbia University, with which I am connected, started a course of electrical engineering in 1889 which was not part of mechanical engineering or of physics. It was as distinct as any other course in the university. We took that stand 18 years ago and have had no occasion to recede from it. I think there is a strong tendency for others to take the same position.

Professor Norris in his history of the development of electrical engineering education in this country overlooked the fact that we have courses which are specifically electrical engineering, and not appendages to mechanical engineering or physics.

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* Such an Educational Committee has since been appointed.

In Professor Karapetoff's paper, what he advocates is not only very radical, but opposed to the whole history of education, which from the very beginning has dealt first with the simple and later with the complex. When I say " simple ", I do not mean necessarily the most easily understood, but the idea involving the fewest things to think of at one time; that is, principles should precede practice. I think this is natural in education. It certainly is the historical method. Furthermore, we have experience bearing upon that point. Take an institution like the Troy Polytechnic—which for many years taught theory almost exclusively with very little laboratory or other practical work. That institution has been successful and has turned out a number of eminent engineers. While it may have modified its course somewhat recently, this experience shows that it is possible to turn out successful engineers on this plan. Perhaps that is going a little too far, but it shows it is possible to do that. On the other hand, the trade-school, which deals with practical matters almost entirely, is very well in its way, but it does not produce the highest intellectual results.

Furthermore, we must have some sort of a *pons asinorum*, for weeding out the incompetent men. I think that we should not make it too easy, or too pleasant, to get into the electrical engineering profession. At West Point, for example, the cadets are made to do exactly what they don't want to do. That is what a man should be taught to do. This leading a man by the hand to pleasant places does not meet my approval; in professional education a student cannot learn electrical engineering by sitting in the park and looking at beautiful scenery. That is too easy. A student must be capable of abstraction; he must be capable of self sarcifice; he must do the very thing he does not like to do, and do it well. I consider West Point the best technical school in the world, and in itself a very strong argument in favor of technical education.

I do not agree with the contention that subjects like chemistry, physics, mathematics, and mechanics, should be taught by engineers, especially electrical engineers. I do not object to a teacher having an engineering interest, a man with a high opinion of engineering, but if he is an electrical engineer, and teaches chemistry, mechanics, or physics, he will teach those portions which he *thinks* are important. He may be right at the time, but perhaps five years from then the whole situation changes. I believe in teaching chemistry, physics, mechanics, and mathematics for themselves, and not picking and choosing; if properly taught these subjects the student will be well equipped and can talk on equal terms with other men who have been taught these general subjects.

Gano Dunn: I wish to express satisfaction with the policy of the Institute developed in recent years, of devoting so much attention to the subject of engineering education. It has been said that the civilization of a nation may be measured by the height of the plane upon which it places its women; it is equally true that the proficiency and accomplishment of a profession is in direct proportion to the attention it gives and the respect it has for its educational influence, to the importance it attaches to its universities and colleges. It was a refreshing address that President Hadley of Yale delivered at the dedication of the Engineers' Building in New York. He said if there was any thing that made the nineteenth century different from all the centuries that had preceded it, it was the accomplishment of the engineer—never before in the history of the world had human beings had so much control over the materials and forces of nature, and the result of that control was transforming all human activities. He went so far as to imply that before long the most successful merchant would be the merchant-engineer, the most successful mayor of a town the mayor-engineer; the most successful statesman, if you will, the statesman-engineer. There is something in the method of an engineer's mind that is direct, that goes straight to the truth, and although we have been discussing a code of ethics to-day which implies that engineers are not honest, I believe that they are naturally honest because their contact with nature has led them to expect the truth and when they do not find it, to put the blame on their own methods of investigation. They proceed further with confidence that what they are dealing with is absolute truth, and that if they persist the truth will be revealed. The influence of the engineer is extending to all other callings, and the engineer in the future will exert an influence that he has never dreamed of exerting in the past. Consequently if we are to grasp the glorious future which has been outlined for us, many of us believe we cannot give too much attention to the methods by which we educate our engineers.

Professor Karapetoff's paper interested me extremely because of his concentric method of instruction. I have little cause for complaining of the methods under which I was instructed, but I feel with Professor Crocker that the plan Professor Karapetoff outlines is too radical. I think, however, that our existing methods could be profitably modified to include many of his ideas. For instance, it would have helped me enormously while I was a student if I had had some person in the capacity of a kind friend at college to give me the relations which the studies I was pursuing bore to other studies and to the activities of the world. Instructors are supposed to do that, but because each man is devoted to his specialty, very often he does not do it. I really think we could profitably establish in our universities a course on the correlation of the student studies, to which might be given a very small portion of time, but that portion of time would be highly efficient. A student could then know it would be worth while for him to study calculus, for the good it would do him. He could have a promise given, on the strength of which he would work hard.

I believe in America we are ahead of Great Britain in technical education. Conversation with the manager of a correspondence school over there revealed that many of his students were obliged to keep secret the fact that they were studying technical subjects. Many of the industrial managers, I have been told, have not had theoretical educations, and they prefer to employ men who have grown up in the ranks of their business, rather than men who have received a technical training. I even know of one Oxford man who wanted to go to Cambridge to take a technical course, and the superintendent preferred he should go straight from Oxford into the factory, feeling that he would do better than if he took a technical training. I can hardly believe it, but it is true.

I should like to expose my ignorance of the law by giving it a dig in passing. I believe that engineers have set the pace for progressive training, and as a result the engineering mind, as President Hadley described it, has a great future. We come into contact a great deal with the law in the direction of patents, and in many other directions. It seems to me that progress in medicine, in the arts generally, in all commercial industries, in engineering, and in science has been very great, but that progress has not been as great in the law. The law to-day is more complicated and less satisfactory than it was many years ago, and while it is perhaps idle to discuss the question here, I feel if the engineer uses his influence, whenever he has a chance, to urge the simplifying of legal processes, and expresses his disapproval to lawyers of the complicated processes which they now pursue, and which many of them advocate, some good may be done.

As between a broad general training in a technical school and a specific training which, of course, must be limited to a few subjects, I prefer the former, and this supports Professor Karapetoff's ideas. A man is better equipped for life if he knows the scope of his field, even though he does not know many specialties in it, than if he is made an extreme specialist in a particular portion of the field which he may not have occasion to use. Not only is he better equipped, because he can realize on his time spent at college, but because his general training has broadened him as a man, in a way that the special training would not do. I hope every convention will have some educational papers, and that we will all take pleasure and pride in supporting our universities in every way we can.

William Esty: A number of the subjects brought out at this session seem to me to warrant the adding of some papers on technical education to our convention programs. I agree with Professor Karapetoff that in dealing with young men, say at the college age of eighteen, there is necessity for giving them something concrete to take hold of on which to build up the theory. I think that is the natural order of development in the child; and with college students some attention must be paid to the natural order of their development. Professor Crocker in discussing this matter, spoke of beginning with principles because they were simpler than the concrete cases. It seems to me that his idea contradicts the view of Herbert Spencer, who speaks of principles as being a conglomeration of concrete things, and of a principle or law being essentially more complex therefore than any one of the concrete facts on which it is based. It seems to me that that is a valid definition of a principle—an aggregation of concrete facts which have finally been formulated into principles from experience. Principles then are more difficult to teach to a freshman than isolated concrete facts; so I think we should have something of the concrete to give him also.

I am going to outline briefly how at Lehigh University we try to accomplish the object of giving the students an idea of some of the concrete facts on which engineering is based, and at the same time give them some theory also. At the end of the freshman year the mechanical and electrical engineers take what we call our " summer school in constructive elements of mechanical and electrical apparatus ". The summer school lasts only four weeks, and the students are at work for three hours in the morning and three hours in the afternoon. In that rather brief time we attempt to acquaint them with the elements of mechanical and electrical engineering. For instance, in the electrical end of it, in which I am especially interested, we have them dissect circuit-breakers, rheostats of different types, disassemble motors and generators, lightning-arresters and transformers, and sketch the circuits. We do not attempt at first to teach them the complete theory on which all this apparatus is based, but rapid progress results by having them acquainted with the actual things. We find this plan very advantageous. We have tried it now for six years, and if there is anything in the old adage that " The proof of the pudding is in the eating ", we can show that this pudding has proved good with us. We find, as a matter of fact, that the mechanical and electrical engineers who have taken this supplemental course in concrete facts, with a little theory mixed in on the side, are much better able to grasp the theory of the dynamo and of the transformer later on in their course than are, for example, the civil engineers who do not have this summer school work. We find it saves time in the long run. Our object is to concentrate in that four weeks an experience with the things themselves that these young men might take a year or more to acquire without it. I am not sure whether we are unique in this respect among colleges and universities, but if there are any others that have had similar experience I should like to hear from them.

In summing up this controversy of theory versus practice, it strikes me that it is after all another phase of the old question as to whether we should have classical education or technical education and as to which does the most for the young man. We have heard this thing wrangled over now for twenty or thirty years, and the end is not in sight. I think both sides of the controversy can certainly come to a common ground if we conclude that what after all is the object of education is the training of a young man to think for himself, and that implies, of course, a knowledge of how to solve problems when they arise. We cannot possibly teach all problems to a young man in college, but we must ground him in fundamental principles, giving him theory even at the expense of practice, so that when he leaves college he will have training which will enable him to solve almost any problem. That, I think, is the aim of technical education.

G. W. Patterson: As a member of the committee of the University of Michigan on reorganizing our course, I have taken part in a great many consultations as to what a technical school course should include. I must admit that the trend of the work by our committee has been entirely away from what Professor Karapetoff has given us to understand is his notion of the proper thing. We feel that a man who goes to a technical school is a crude product and that there are many things which he ought to study to make him an educated man before he takes up engineering as a specialty. Without modern languages, without drafting, without a thorough grounding in mathematics, physics and chemistry we feel no man is competent to understand the elements of any kind of engineering, to say nothing of electrical engineering. I am of the opinion that there are some germs of truth in what Professor Karapetoff has told us, but if we examine his paper closer we find that if we adopted his ideas we would in my opinion make a sort of plaything of engineering. Instead of a real training, which should be given to men who are to occupy these important positions, the actual training would fall far short. The engineer should be an educated man; he cannot be educated in a specialty that ignores the elements which go to make a broad education. With us the trend is rather toward a six-year course than to cut off the things which we find necessary to teach in the first year or two under the present plan. In the University of Michigan we have six-year combined courses in which a man registers in the department of literature, science, and the arts, and also in a professional department. At the end of four years he receives the degree of bachelor of arts, and at the end of two years more either that of doctor of medicine, or bachelor of laws. In the engineering department the trend is toward the same thing; that is, a longer course in which we do not cut out the modern languages, or reduce the amount of physics and chemistry in the period of training, but put them in earlier and put in other things. There should be no opportunity for a man to learn engineering without a proper foundation. Omitting the foundation, is like trying to build a mansard roof first and put on the foundation the last thing.

If Professor Karapetoff's paper be taken seriously, it would, I think, tend to destructive rather than to constructive teaching.

Lester W. Gill: I am interested in this subject, because I have been endeavoring for the past few years to develop a course in electrical engineering in one of the Canadian universities. I am in sympathy with a number of the opinions expressed, but I do not think that it is practicable to introduce the radical changes suggested by Professor Karapetoff. Referring to his proposed schedule, it is noted that mathematics is omitted entirely from the work of the first year, and very little is set down for the second year. My experience has been, not only in my own case but in the case of students in my classes, that if mathematics is dropped even for one year before the student is acquainted with its practical applications, he loses his grasp and consequently his interest in the subject. To most students mathematics is a dry subject unless it is presented in an interesting way; but even admitting that many findit uninteresting, it involves a certain amount of discipline which is quite necessary.

I quite agree with President Sheldon that the greatest difficulty lies in the presentation of the subject, and in my own work I have endeavored to make the elementary subjects practical as well as theoretical. This results in a compromise between the standard college schedule and that proposed by Professor Karapetoff. In this way the elementary subjects—mathematics, physics, and chemistry—can be made as interesting as the purely engineering subjects. As a student I found mathematics the most interesting subject of the whole course, because the teacher knew how to make it interesting. To make these subjects interesting the student should be given examples of the practical applications of the subject as he proceeds, and these examples should deal with things with which he is familiar. This arouses his interest in the theoretical side of the subject and he at once realizes its value. As an illustration, take the case of a student in physics trying to master Ohm's law. If this is presented to him merely as an abstract natural law, he will not find it very interesting, and will consequently get only a superficial conception of it; but give him an illustration of its application; ask him to calculate the voltage at the end of a given trolley line, given the distribution of current, and it will be found that after solving this problem he will look upon this law from an entirely different standpoint.

The above illustrates what I mean by making the elementary subjects of a practical nature. My own opinion is that the weakness in our engineering schools lies in the method of teaching rather than in the arrangement of the schedules. The aim of the teacher should be to develop the student's ability to reason for himself, to think logically rather than to memorize rules. When a student can take the initiative and reason things out for himself, the technical school has done all it can to make him efficient from a technical standpoint.

L. D. Nordstrum: Referring to Professor Karapetoff's paper—this proposed method is in a sense radical, but I cannot help but agree with him in part. I do not think that the students should have mathematics and physics and kindred sciences taught by engineers. It is well if we can have mathematicians introduce as far as possible the engineering subjects, so as to make them interesting to the student, but for the teaching of these subjects thoroughly we must have a professor of methematics and a professor of physics, etc., who are, so to speak, specialists in that line. The time is here when the trend is towards specialization, and no man can hope to have the strength of a thorough mathematician, a thorough physicist, thorough engineer, etc., all in one. The student must get these from individual instructors who devote their entire time to their particular subject.

I believe that we can not expect to turn out a finished engineer from our universities. I think all that we can hope to do is to take our student as he enters the college and direct and train his mind properly in the fundamental principles, giving him a good foundation upon which to build. I think it is too much to expect a student in a four years' course to gain all that is gained and can only be gained in the practical pursuits of his profession. It is my opinion that a man has never finished his education; his entire life is that of a student. His university years are merely the starting or foundation years.

V. Karapetoff: In reply to Professor Crocker's remarks, I would say that, of course, the instruction should proceed from simple to complex; the point at issue is what to consider as simple and what as complex. This to my understanding varies with time. Twenty years ago it would not have been simple to begin the freshman year with instruction in street-car propulsion and incandescent lamps; but now this is much simpler for the student than an instruction regarding the properties of magnetic poles. We now see street cars and electric lights much more than magnetic poles. Professor Crocker mentioned trade-schools, and I understand him to favor the opposite, or the theoretical courses. I am not in favor of the trade-school idea, or of a theoretical-school idea. I am in favor of the *psychological* idea. Our president and some other speakers compared the student with raw material; there is however a great difference between raw material in a manufacturing sense, and a man. A man is a thinking being, and if you try to make a machine out of him, he kicks at first, and then withers intellectually. The analogy to a machine should not therefore be carried too far.

Mr. Dunn said that my method is very radical. Perhaps, it seems radical for electrical engineers, but it is not considered radical at all among our best educators. It is an already acknowledged fact among our primary and secondary schools. I simply transplanted the psychological ideas that are in use in the primary and secondary schools in this country, schools of which we have good reasons to be proud. With me it is primarily the question of assuring a coöperation of the student. If you do not agree with teaching electrical engineering in the freshman year, there still remains this point--that the cooperation of the student is not secured with the present method of instruction. Hence, you must change your method so as to secure his coöperation. He is a thinking being, he is supposed to enjoy his life while in school, and not simply live in expectation of the things which may come after he has left the school. Professor Crocker thinks that unpleasant things must be connected with the education of young men. I agree with him, and wish to assure him, that even with the concentric method there will be enough left to make the life of a student more or or less unpleasant. Professor Crocker objects to mechanics, physics, mathematics, and chemistry being taught by engineers from the engineering standpoint. Surely they should not be, at the *advanced* stage, but at the elementary stage, in order to connect them with the engineering profession. In the courses of studies which I give in my paper, I propose that mathematics and mechanics should be taught in the second year by an engineer.

President Sheldon mentioned expository ability and the raising of salaries of professors, as more needed at present than a change in methods of instruction. I do not quite see how the concentric method could prevent a raising of salaries, or affect the necessity for expository ability on the part of the teachers.

Professor Patterson thinks that I am opposed to general culture. On the contrary, if you will kindly look into my courses of instruction you will find a considerable amount of time devoted to general culture in the first two years. I do this not only for the sake of general culture in itself, but also in order to give the student an opportunity to select intelligently his profession, before he goes into the details of it. This is more important than the general culture, as now understood. It is time to stop calling a study of mathematics and mechanics or even languages in their dry, abstract form, as "general" culture.

In presenting this paper I had in mind two purposes: to criticize the present system of instruction, and to give a new, improved method. Even if the concentric method is no good, there still remains for you to answer the criticisms against the present system, and to develop a better system.

Charles F. Scott: There are some dozen points which I had in mind to bring up, but I will forego doing so at the present time. I will refer to one point however, the statement made a little while ago that the method proposed by Professor Karapetoff would be opposed to the whole history of education. Is not that one of the best recommendations it has? Has not the history of education for the last fifty years been one of advance? Not long ago new sciences were proposed instead of old languages. Then science was degraded by being applied to engineering. Then engineering ceased to be theoretical, and laboratories and machine shops found their way into colleges. Educational ideals and methods have been changing. We have not reached perfection. Engineering methods must be applied to the teaching of engineering, and that means development. Possibly, therefore, one of the best recommendations of this proposed system is that it is radical and is opposed to old ideas. If it is not quite the right thing it is getting closer to it and it merits careful consideration.

I wrote down two words on this slip of paper a moment before Professor Karapetoff mentioned the same words "educational committee. Accepting the suggestion of Professor Karapetoff as a motive, I am very pleased to second that motion; namely, that the Board of Directors of the Institute be requested to consider the advisability of the appointment of an educational committee.

V. Karapetoff: I shall be very glad to make such a motion. (The motion was put and carried.)

J. J. Carty: A few years ago I would have been quite ready to submit a number of criticisms on our technical schools. But the more information I get upon the subject and the more attention I pay to it, the more difficult it seems to be and the less ready am I to criticize. During the past twenty years I have received into my office a very large number of graduates from the principle technical schools in America, and from this experience I am able to make two generalizations. They are these:

1. That the best men do not all come from one school. The personal equation is so overwhelming that so far as my experience goes, the efficiency of the school from which the men graduate cannot be determined by the relative efficiency of the men themselves after graduation.

2. As a rule, the men are well trained technically but are very often defective in respect to that broad and liberal training which should underlie the technical education of every professional man. This defect is a serious one and very difficult to overcome. I have almost come to the conclusion that it is hopeless to attempt to give in the technical school the necessary broad and liberal foundation studies, and at the same time keep up the arduous work required of the student in connection with the strictly engineering studies. I am coming to the state of mind where it seems to me that the introduction of these so-called broadening studies into the curriculum of the technical school might fairly be likened to the introduction of such studies into a medical school.

As the general scheme of education in this country stands at present, I think that the electrical engineer, for the foundation of his liberal education, must depend solely upon the scientific studies themselves, or pursue his broad studies either before or after his technical course. Helpful as the scientific course is in the development of the student when forming part of a liberal education, it alone is not sufficient if the engineer is to take his place in the world, as he should, with cultivated men of affairs, whether they be physicians, lawyers or men of business. The engineer should be so equipped that he may attain those ideals so well set forth by President Hadley in his recent address at the dedication of the Engineers' Building, in which he says:

> We have outgrown the day when a little common-sense was sufficient for managing the affairs of the nation. They are become too complex, and this complexity gives the engineer—if he will add to his training in mathematics a training in ethics and political economy and the fundamental principles of the law—an opportunity such as never before existed to claim and receive the position which rightfully belongs to him.

Further on in his address, President Hadley says:

> We celebrate to-day and we are justified in celebrating the recognition of science as a necessary guide in the conduct of the material affairs of each man's business. Half a century hence, when our descendants shall meet in this building, or some yet greater building, I am confident that they will celebrate a yet greater thing—the recognition of the right of men of science to take the lead in enlightening the thought of the people on public affairs and the responsibility of filling the higher positions in the service of the commonwealth.

President Hadley says elsewhere in his address that the course of our technical schools tends to have a narrowing effect upon the student, instead of a broadening one. This is in my judgment often the case. The narrowing effect of this technical training, it seems to me, is a negative one, not due to the technical course *per se*, but due to the fact that technical training is given, to the exclusion of liberal studies. I am hopeful that ultimately our entire scheme of school, college and university training will be modified so as to permit the student to graduate from his professional school at a sufficiently early age, and at the same time have received the necessary liberal education. At present I do not see how this can be done.

How to provide this broad and liberal education and at the same time not encroach upon the legitimate work of the professional school is what I consider to be the problem of engineering education to-day. Until this is settled, I have very little heart in any discussion, such as that pertaining to the relative number of hours which the engineering student should spend in the laboratory, at shop work or at lectures. Once the engineering student has a proper educational foundation to build upon, his professional studies can no longer be said to be narrowing, for these studies would, in the light of a proper philosophy, take on a new meaning. They would become an absorbing, intellectual pursuit rather than a hard and disagreeable task. They would become to a high degree broadening.

With this large question out of the way, I am satisfied that the problem of the make-up of the curriculum of the engineering school could be satisfactorily solved. If these views which I have expressed should prove to be correct, we would still have before us the most difficult question as to what broadening studies should be specified, and that perhaps equally difficult question as to where and when these studies should be pursued.

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PRACTICAL ASPECTS OF STEAM RAILROAD ELECTRIFICATION

BY W. N. SMITH

In view of the extended treatment which has already been accorded to this subject on the floor of the Institute, and elsewhere by distinguished engineers during recent years, it is difficult and in fact hardly necessary to add anything to the electrotechnical side of the subject. So many are the electrical schemes proposed for the accomplishment of the various ends that it now seems desirable to examine the subject from standpoints other than electrical, in order to facilitate intelligent consideration of the problem as a whole.

The trend of some of the papers that have recently been presented, and the discussions that have accompanied them, convey the impression that electric railway engineers are ready to apply any one of several well developed systems of electrical propulsion to any railroad, and attempt to make it pay. Although much has been published, most of it is of so general a nature that it is only partly convincing; and while it doubtless stirs up professional enthusiasm and tends to keep up active emulation in devising attractive schemes and systems, the railroad man with a particular problem to solve is almost as much in the dark as ever as to the practical value of the new motive power for his particular conditions.

Although at first sight there would seem to be as many different types of problem as there are railroads to be electrified, the writer believes that some general classification is possible; and while it might be further specialized by paying especial attention to topographical and transportation features, which may be distinctly peculiar to each individual case, the writer thinks that railroads in general could be classified as follows:

1. Suburban lines or sections.
2. Tunnel and terminal sections.
3. Heavy trunk lines with low grades, dense traffic, and more than two tracks.
4. Double-track trunk lines with grades under one per cent.
5. Single-track trunk lines with grades under one per cent.
6. Mountain railroads with single or double track, with long grades steeper than one per cent.
7. Single-track branch lines or feeders.

It would seem that a large proportion of the railroad mileage of the country could be included in some one of the above classes, and there are individual railroad companies which have mileage under all of them.

The question of density of traffic is often brought up in discussions of steam railroad electrification, and it is generally admitted that the problem deals with the economic effect of increasing the train movement; but the physical features involved in the study of train movement are so difficult to define in general terms, and the number of concrete cases is so infinitely great, that very little information has been gathered or classified that will enable general rules to be made for determining where, so far as train movements are concerned, it becomes economical to abandon steam in favor of electric motive power. It seems to the writer that this very complicated subject must be approached by degrees, and upon the basis of concrete illustration drawn from examples of conditions as classified under the above suggested headings. Such a treatment of the problem in general would make it more attractive to those charged with the practical management of railroads—the men to whom general curve sheets, which appeal to theoretical electrical considerations, are apt to be meaningless unless accompanied by voluminous explanation. As generalities, solutions by curve sheets are usually of very limited application.

The fact has recently been emphasized that hitherto steam railroad electrification has been carried out only in very special problems, coming mostly under the headings: (1) Suburban, (2) Terminal, and (3) Heavy trunk lines, in the above classification, but only for relatively short sections. Considerable attention is now being given to problems of the class under (6) Mountain-grade division, and one such project is actually under way in this country.

The electrification of a portion of the Erie Railroad Company's Rochester Division, could properly be classed as that of a feeder or branch line under (7), but even that, as at present constituted, is only a partial electrification, as only passenger traffic of the suburban or interurban type is handled electrically at the present time, steam power still being used for through passenger and for all freight service. The West Jersey and Sea Shore electrification should also be put in this class, though an enormous summer excursion business is its principal justification.

Furthermore, the writer believes that in discussing a problem of such tremendous proportions, the matter of the particular electric system to be employed should not necessarily be placed foremost, but that practical railroad operating conditions must be regarded as of paramount importance. It is, of course, impossible to cover the whole field in a paper as short as this is intended to be, but it is certainly in order to get a larger perspective upon the activities of the railroad as a whole, rather than to keep our attention focused upon the purely electrical part of it.

The fields of activity concerned in the electrification of a steam road may be subdivided into two broad divisions.

1. The electrification project, as it calls for the services of the manufacturer and the engineer.

2. Railroad operation, which in this connection may be considered as threefold:

a. Financial or economic,

b. Railroad construction or standardization, and

c. Transportation or operative.

Reviewing these divisions, the electric railway industry occupies a peculiar position as compared with the general trade in railway appliances.

A practical monopoly of electric propulsion apparatus is divided among a very few large companies. This is somewhat similar to the general situation as regards steel rails, and steam locomotives, both of which commodities are produced by a relatively small number of manufacturers. Until recently the steel-rail situation was kept very close to a uniform standard in quality of product, as well as in price, but there having been a strong protest by the railroads against the defects that have been developed in quality, this feature is now undergoing revision by the steel companies. With respect to locomotives, however, more liberty of action is preserved by the railroad companies. The requirements of the motive-power departments of different railroads are so diverse as to afford little opportunity for wholesale standardization, which is a matter that is left entirely in the hands of the railroad customers rather than with the manufacturers. There are certain tendencies toward standardization on a large scale, such as that made possible by the associated Southern Pacific, Union Pacific, and allied lines east and west of the Mississippi, for the sake of securing economy in maintenance and operation; but such attempts as have been made toward standardization on the part of the locomotive manufacturers seem to have pertained more to certain interchangeable parts of the locomotives, than to types which have usually been developed by the needs of individual roads. With electrical motive power apparatus, however, the art is relatively much newer, and the number of trained specialists is fewer, and mostly concentrated at the manufacturers' shops so that the opportunity afforded the manufacturers to inspire and direct the formation of their customers' ideas on electric propulsion has not been neglected. It has had a great effect upon the development of the industry.

This does not mean that the manufacturing engineers' judgment may not be excellent concerning questions pertaining solely to the design of the apparatus intended to meet particular conditions. It can hardly be expected, however, that manufacturing engineers can always look upon their apparatus in any other light than that of a special commercial product, the responsibility for whose performance comes home to themselves in particular, they are therefore prone to consider the various conditions of construction and operation from the standpoint of the effect of railroad conditions upon their apparatus as more important than the sum total of effects of the apparatus upon the railroad problem as a whole.

In general, standardization of any railroad equipment on the part of manufacturers is more usual in commodities which the railroad companies cannot or do not ordinarily manufacture themselves in their own shops. Railroad companies have been compelled to leave to steel mills the work of making the rails, but they have frequently made a practice of building locomotives in their own shops. Their necessary repair-shop facilities place them in a position to furnish for their own locomotives and cars whatever equipment a locomotive manufacturer or car builder may decline to furnish. It is quite possible that some years hence railroads will devise their own systems, and build their own electric motors and locomotives. There is even now a tendency in this direction by the large trolley railway companies who make many of their own electrical repair parts. The Standardization Committee of the American Street and Interurban Railway Association has made an excellent beginning along the same general lines as have been followed in years past by the Master Mechanics' and Master Car Builders' Associations of the steam railroads; and in the course of time it will undoubtedly come to pass that advances in standardization will emanate not so much from manufacturers' engineers as from the railroad companies' own electrical engineers, who will be held directly responsible for the results.

By the time that twenty or thirty roads have electrified their lines, wholly or in part, the attitude of their operating and maintenance engineering forces may become an important factor in the situation; and the commercial rivalry now shown in devising and perpetuating electric systems will then be diverted from its present tendencies, toward the more natural function of competing to furnish apparatus as specified by the railroads.

The consulting engineer's standpoint at the present time is that of an interpreter between the manufacturer and the railroad. He has to translate the limitations of the electrical apparatus in terms easily understood by railroad officials, who generally do not pretend to be electrical experts; and he must be sufficiently familiar with railroad standards and practice to insist that the electrical manufacturer shows due regard for the general fitness of his apparatus to railroad purposes, both in design and reliability. He is frequently charged with a very grave responsibility in aiding the railroads to decide some very fundamental and perplexing question arising from the relationship between the old art and the new. Although he may write new and complete specifications for all the parts of manufactured apparatus involved, he is generally not called upon to design it in detail, as that function is still practically monopolized by the manufacturing companies, though subject in some degree to the consulting engineer's control. He has not only to act as mediator between the railroads and the manufacturing companies, but he must also secure coöperation between the various departments of the railroad itself which are intimately concerned with the work he is doing; that is to say, the construction, maintenance, mechanical, and transportation departments—all of which, in many instances, have to be consulted with reference to a single detail. The pioneer engineering work of steam railroad electrification, up to the present time, has largely been done on the initiative and with the aid of consulting engineers, whose usefulness to the railroad in the above described capacities has been very notably demonstrated.

The standpoint of the railroad management as above suggested comes under three general heads; the financial or economic, the constructive and maintenance, and transportation.

The control of a railroad being in the hands of those who represent the investors, the financial aspect of any improvement is the first to receive consideration. The financier looks upon the problem of railroad motive power as only one of a large number to be solved from the standpoint of the maximum possible return for every dollar invested, whether it be for the purpose of reducing the cost of conducting the existing business, or of largely increasing that business. A project for the electrification of a railroad is usually attractive, because of the increased amount of traffic it becomes possible to handle in proportion to the expense of handling it. This is usually directly accomplished by increasing the speed of revenue train-movement over a given piece of track, and by reducing the amount of non-revenue train-movement.

Such questions are, of course, most pressing where conditions of traffic congestion are most severe; and for that reason most of the heavy railroad electrification has hitherto been worked out in and near New York City, where the maximum movement of passenger trains is required in the minimum amount of area available for terminal facilities. The electrification, first of the Baltimore & Ohio tunnel, then the Long Island Railroad, the New York Central Railroad, the New Haven Railroad, and the Pennsylvania Railroad's New York terminal now under construction, was called into being, first of all by public necessity, and secondly by the desire of each railroad company to place itself in a position where it could handle at its terminal the maximum traffic that its lines and territory could develop, steam motive power having for one reason or another reached its limit. These installations are distinctly special in character and can hardly be taken as representative of the general railroad electrification problem, although the general principle of increasing net earnings by increasing capacity is of universal application. In much of the work referred to about New York City, the prospect of immediate returns upon the investment had to be considered as of secondary importance. But in proportion to the total mileage of the country which may ultimately prove fit for electrification, territory of such a character is relatively small in extent. Tunnels and terminals like those mentioned have been electrified simply because of the physical impossibility of meeting the business and public necessities in any other way.

The more general cases, however, are not likely to be regarded by the financier in quite the same light, although it is believed that they can be more convincingly solved on their financial merits alone than is possible in the case of expensive metropolitan terminals. Each case that is brought up for solution must, through careful detailed estimates, justify itself on its own merits, as affording facilities for making transportation more profitable.

When the railroad man is looking at a transportation problem from the constructive and maintenance standpoint, he has in mind the crystallized experience of some 70 years of steam railroad practice that has resulted in the development of railroad equipment along certain lines, which, generally speaking, are rather conservatively maintained. It may be well to recall the fact that the steam locomotive of the present day is in its essentials practically the same machine that was developed by George Stephenson; that is, it comprises a horizontal multitubular boiler with a fire-box at the rear and smoke-stack at the front, and the wheels are propelled by a direct-coupled, high-pressure engine, which increases the rate of combustion of the fuel by discharging its exhaust into the smoke-stack. Similarly, the passenger car has been developed from the old omnibus. A departure from some previously recognized form is often found good, but there is nevertheless considerable resistance to change. In justice to steam railroad men, however, perhaps it should be said that opposition to new forms is not likely to be so great because of radical difference in themselves, as because of the great cost of keeping on hand a line of repair parts entirely different from those which their present historic equipment obliges them to carry in stock. This, of course, pertains more especially to rolling stock and track material. Most railroads have worked up a line of standard parts of equipment, and the Master Mechanics' and Car Builders' Associations have coöperated extensively to promote the use of these standards upon all the railroads, and there will naturally be considerable opposition to any disturbance of such standards. Although the electrical equipment will necessitate, for its own maintenance, the addition of a considerable quantity of repair stock, it should not without good reason be permitted to change any previously existing standard that it is desirable to keep. On the other hand, there may be some very fundamental reasons for changing existing standards in order better to accommodate certain electrical features. An instance of this upon a certain railroad was the adoption of a new shape of splice-bar, specially rolled, to accommodate a heavy rail-bond underneath it, upon a section where some new track was to be laid; while the objection of another railroad to increasing the diameter of a motor-car wheel on account of the additional size of tire that would have to be carried in stock eventually resulted in the retention of an electric motor originally adopted for a lighter car. At first the motor had been thought too small for the increased duty which was to be imposed upon it, but was found to be adequate when fitted with suitable means for increasing its capacity, thus satisfying the desire of the railroad for the maintaining of standards in its equipment and at lower cost.

The question of clearances has often been most perplexing, particularly as regards the location of either third-rail or overhead trolley construction. The stationary features pertaining to the right of way, and the dimensions of moving equipment, must not be allowed to interfere with each other. The third-rail sometimes conflicts with bridge-gussets on the one hand, or with hopper-bottom coal-cars on the other. The use of third-rail also makes more necessary the elimination of highway grade-crossings, and requires careful attention to the protection of the public at station platforms. Low overhead bridges conflict seriously with trolley construction, particularly when high voltage is desired.

High-tension trolley construction introduces, among other problems, the purely mechanical one of providing suitable warning signs or ticklers for trainmen on the tops of freight cars; these must not only be light enough not to injure brakemen, nor damage the trolley mechanism on moving equipment, but must also be heavy enough to withstand the blows they receive from the trolley without being broken or rendered useless.

Either type of construction may require special and often expensive arrangements at drawbridges. The civil authorities in cities sometimes arbitrarily insist upon placing high-tension lines underground, which is always expensive. Telegraph and telephone lines have to be protected from mechanical and electrical interference. These are a few of the characteristic problems that arise with each electrification scheme, but solutions of them do not appear on the mathematical curve sheets with which professional papers are sometimes illustrated.

Looking again at cars and locomotives, the steam railroad man will commonly take his standard coach as the point of departure, and suggest at the outset that it be equipped electrically practically as it stands. Here it is entirely in order to remark that the main object of electrification is to facilitate traffic. The car bodies themselves should be built with that end in view, in order to get the full benefit of the superior type of power. The object to be attained affects the dimensions of the vestibules, doors, and seats, as well as the length of the car, and even the form of roof of the car may be altered from standard types without detriment to passengers, if external conditions make it desirable. Suburban service is the type of service that admits of the greatest modifications in this respect; and that car is likely to be the most popular with the patrons of the road which is so built as to enable freer ingress and egress of passengers, a matter which should not be lost sight of where there is competition between different lines to be taken into account. It is no little tax upon the engineer's ingenuity to get the best results in a new development, and still conform to the general lines of conventional car designs, some features of which have been based upon rules and practices primarily imposed for the greater safety of the traveling public.

Coming now to locomotive design, perhaps the most fundamental advantage which an electric locomotive has over its steam predecessor is greater mechanical simplicity, particularly as regards translation of the tractive effort from the motor to the wheel-rim. The absence of reciprocating parts is advantageous to a high-speed electric locomotive for passenger service, because of the lessened vibration of the locomotive itself, and the greater diminished wear and tear on the track. In the case of a slow-speed electric freight locomotive, the uniformity of tractive effort in hauling heavy train loads is a very desirable feature, particularly at starting. The tendency towards simplification and elimination of reciprocating parts has caused the concentration of great weight at a less height above the rail than is usual for a steam locomotive of equivalent power; and this lowering of the center of gravity is not without its effect in running conditions at high speed, particularly upon a curved track. Steam locomotive men regard a high center of gravity as advantageous rather than detrimental, because its longer leverage from the top of the rail, which is the fulcrum, eases the side-thrust against the rails, due to whatever centrifugal force or lateral vibration there may be. So confident are steam engineers that this is a cardinal point of superiority that they express a desire to see electric locomotives so built that the essential difference between a steam and electric locomotive will consist in the replacement of the boiler upon the locomotive frame by an electric motor, in order to keep the center of gravity at something like its present height. If electric locomotive designers in this country keep as clear of the use of side-rods in the future as they have in the past, there does not seem to be much chance for increasing the distance of the center of gravity from the track to the height it frequently reaches with a steam locomotive; but in Europe some of the latest and most successful electric locomotive designs show a tendency to set the motors above the driving wheels, two motors being used to drive three axles through side-rods. The mechanical excellence of workmanship of these locomotives has been attested by some of the foremost electrical engineers of this country who have seen them. Whether or not the tendency of this design will persist, will depend upon how applicable this method of coupling proves to be to the loads and speeds met with in this country.

The latest developments in American locomotive practice as exemplified by machines actually in commerical operation or under test show three types: first, that of which the driving-wheel base is rigid, as in the case of the New York Central and the St. Clair tunnel locomotive units, the former having pony wheels, the latter none; secondly, the articulated or bogie-truck type, with two large driving trucks pivoted to the locomotive body, each truck carrying a large motor on each axle; and a third type, now being tested by the Pennsylvania Railroad, which is built upon a locomotive frame of standard type, borne at the rear upon the outside journals of two large driving axles, each carrying a 500-h.p. motor, the forward end of the frame being carried upon a four-wheeled bogie truck generally similar to that commonly used with the American or Atlantic type of steam locomotive. This particular sample is designed primarily for single-phase traction, and a transformer is carried over the bogie truck but not at a relatively great height above the rails. The superstructure of each of these locomotives is a steel-plate cab or enclosure housing the engineman and the control apparatus, but in no way approaching the weight of the boiler mounted upon the frame of the steam locomotive. The third type above described has appealed to steam locomotive men as conforming more nearly to their preconceived ideas of locomotive construction, but it remains to be seen whether American designers will work out any method that will result in further lifting the center of gravity along the lines followed by the latest European practice.

Railroad electrification invariably raises questions of safety to the traveling public. Both the third-rail and the trolley are frequently described in the daily press as "deadly". The fact that on a third-rail system a bad short-circuit can take place without blowing the station circuit-breakers, which have to be set for heavy overloads, sometimes results in serious blockades. When the damage is done it is usually expensive, and takes time to repair. In the case of a high-tension trolley system only a small leak is sufficient to cause a short-circuit, and the amount of actual damage done thereby is trifling. Such troubles as may be developed by short-circuits are generally not of long duration; whatever wires or cables are burned in two are burned quickly, and clear themselves promptly. With a high-tension system there is no possibility of confusion between an overload and a short-circuit.

Another feature of the question of safety involved is the dependence of a large number of electrical transportation units upon one power station as opposed, in the case of steam transportation, to an equivalent number of entirely independent units. It is perfectly possible for a disabled electric train to ground or short-circuit the line in its own vicinity in a manner that will prevent other trains from approaching. This is not the case with steam locomotive trains, as the terrible record of steam train collisions bears witness. Generally speaking, the combination of electric propulsion with the block-signal system for protecting trains has not been developed, though in the early days of the art the matter was occasionally brought forward as additional argument in behalf of electrification. The paramount desire to keep all traffic in motion has militated against the idea of permitting the disabled train or line-section to hamper in any way the movement of other trains on other sections. It is evident that there are possibilities along this line, particularly in the case of high-tension systems, that can justly receive further consideration, because with the smaller currents flowing in high-tension systems, control of them at a distance is relatively easier than in the case of the heavier currents in low-tension systems.

We now come to a phase of the question which in the writer's opinion is probably the most complicated and least understood of all; namely, the standpoint of the railroad operator or transportation superintendent, and his organization, upon whom the railroad depends for maintaining its earning power. It hardly need be said that the transportation man has it in his power either to make or mar the earning capacity of a railroad, and no matter what facilities for increasing transportation capacity are furnished by the management, the duty of making them pay dividends devolves upon the operating department. The business of a railroad being primarily transportation, and transportation being the special function of the operating department, we here come in contact with the highly trained specialist, upon whom falls the burden of getting the traffic over the road whether it be level or hilly, straight or crooked, single or double track.

It is conceded by all, that the great thing to be desired in a railroad of given proportions is capacity for train-movement. The capacity of a double-track road is stated to be in general, about four times that of a single-track road, general conditions as to grade and location being equal; but as more than seventy-per cent. of the railroad mileage of the country is single track, the most universal problem of increasing track capacity by electrification will apply to single-track rather than to double-track lines. This, of course, excepts terminal and suburban conditions, but includes the majority of mountain railroad conditions where double-tracking is sometimes a physical impossibility.

On the greater proportion of single-track railroad mileage, trains are handled by the telegraphic train-order system under the control of train dispatchers. On some railroads, however, block-signal systems are installed to facilitate the movement of trains, as much time is thereby saved by each train in getting the right to pass from one block to the next. According to a report by the Interstate Commerce Commission, published about March 1, 1907, the total number of miles of railroad lines which had any block-signal system at all was 143,615, of which 48,743 miles was actually equipped and operated by some form of block-signal system. Of this 48,743 miles, 6,826 were operated by the automatic system and 41,916 by one of the several forms of non-automatic system. Of the mileage controlled by the automatic system, 2,032, or somewhat under one-third, was single track. Of the lines controlled by non-automatic signals, 33,585 miles were single-track lines, making a total of 35,617 miles of single-track railroad in the United States controlled by some form of block signal. The total mileage of single-track lines in the United States is estimated at about 200,000, so that about 17.5 per cent of the total single-track mileage is controlled by block signals at the present time. Inasmuch as the operation and maintenance of a block-signal system is undoubtedly cheaper per mile of road than the total annual cost that would be incurred by electrifying, it would appear that the first step in increasing the capacity of a road is to establish a suitable block-signal system. Thus from a practical standpoint the mileage of track where electrification could profitably be considered under present conditions would be greaty reduced; but when the increased capacity created in any instance by a block system has been fully utilized, a further increase is still possible by the use of electric motive power.

Engineers familiar with the interurban trolley development of the past ten years are aware that most lines of this type dispatch their trains very largely by the telephone system. Generally speaking this method works very well, though on the more highly developed systems it is combined with some of the features that have been standardized by the rules of the American Railway Association, and adopted by practically all the steam railroads. It must be remembered, however, that conditions on trolley roads are somewhat different from those on steam roads. The vast majority of the trains are light passenger trains of one car each, stops are of shorter duration, and the speed of all trains is more nearly uniform. The distance between turnouts is less. The penalty of a wreck due to misunderstanding or miscarriage of orders is, generally speaking, much less with the average interurban trolley road than with the average steam railroad; and trolley railroad operators are correspondingly more willing to run the risks incidental to dispensing with the system of transmission of train orders, which experience has shown to be necessary on steam railroads. The meeting points are generally much nearer together, and a block system of any kind would cost relatively more to maintain and operate in proportion to the business done than is the case with steam railroads. At least there seems to be some such motive preventing the universal adoption of signal systems by trolley roads. In any event, it is not at all convincing to a steam railroad man to point out to him the apparent ease with which trains at frequent headway in opposite directions are handled with single-track trolley roads, as a reason why the same course should be adopted by steam railroads in order to increase the rapidity of train movements. Although it is undoubtedly true that the telephone is used extensively as an adjunct to standard methods of dispatching steam-railroad trains, railroad managers generally do not seem disposed to supersede the method developed by the use of the telegraph, except in the relatively small amount of mileage protected by automatic block signals.

Whether the telegraphic train-order system or one of the other systems of block signals be used, the rules governing the operation of trains on steam railroads are very rigid. The telegraphic train orders, emanating from the train dispatchers' office, must be signed by the recipient and the signature telegraphed back to the dispatcher, who then replies " complete " to the various operators to whom he has sent the message as fast as their replies come in. An order restricting the rights of a superior train is more rigidly safeguarded in this respect than an order increasing the rights of an inferior train; and a superior train must receive and reply to its orders before any can be given to the inferior train. Much time may be and often is thus consumed, which may restrict considerably the capacity of a line to handle traffic. Another rigid type of rule is that requiring an inferior train to clear the time of a superior train at a meeting or passing point by not less than five minutes. This holds whether a train-order system or a block-signal system be used. This five minutes' clearance is frequently, for special reasons, increased to ten minutes and often to twenty minutes, thus placing the inferior trains at a still greater disadvantage. Instances of this kind occur when some especially fast express train is operated, where, to insure the greatest possible degree of safety, twenty minutes clearance is provided. The fastest high-speed " flyers " of the present day are thus protected, to the greater safety of the passengers, but to the disadvantage of freight trains. Two such flyers, one in each direction over a road per day, will thus cut down the current of slower traffic over the whole road to the extent of at least forty minutes per day, and frequently more. If an inferior train cannot make an intended siding in time to allow for the required clearance it is obliged to wait on a nearer siding and lose the time required for the superior train to cover the distance between the two sidings, plus any extra time which the superior train may have been delayed. One such delay is more than likely to lead to another, and so the delays pile up into hours during the run intended to be made in ten or twelve hours. If traffic is dense, and sidings far apart, such delays become very serious, and besides the delay to freight, and disappointment and inconvenience to shippers and per diem charges on cars, there is added the overtime due to the employes, which increases the operating expenses. It seems to the writer that conditions of this character are not taken into sufficient account as having a bearing on the subject of electrification for increase of track capacity; and something more than the ability to accelerate rapidly and maintain higher speeds must be given consideration in estimating the increase in the net schedule speed of train movement that at first sight may seem directly to result from the substitution of electricity for steam.

One item peculiar to steam operation which causes delays is the stopping for water. The frequency for such stops will depend both upon the weight of the train, and the grade of the road. Stopping for water sometimes adds to the delays from other causes that have previously held up a train; but for any particular problem the effects of stops for water should be considered separately from stops for other purposes. Where combined with a stop for some other purpose, no marked gain is effected by eliminating the necessity for taking water, unless perhaps three or four engines were to take water in succession.

A case was recently cited of a single-track road in a mountainous country where double tracking would be a very expensive proposition, this road having a heavy traffic in both directions, loaded ore cars coming down and empties going up. It was found in operation that the easiest way to get the traffic over the road was to make every siding a meeting point, that is to say, the road was practically full of trains. The only way of increasing traffic on such a line other than by double-tracking would be to increase the speed of all trains in the same proportion. This might seem feasible enough by electric motive power, but then arises the question whether the increase in speed that could be thus obtained would be sufficient to enable an increase in the daily traffic that would pay a dividend on the total cost of electrification. This would be an excellent instance of a concrete case in which other things than motive power costs alone, of steam and electricity, would have to be considered. In a case of this kind, the capacity of a single-track road would be limited by the speed of the slowest train.

The task of working out the results in such a case is necessarily complicated and would require nothing less than a close study of all the conditions on the ground. The fact that it is impossible to generalize upon the capacity of single-track roads for train movement, renders it equally impossible to generalize upon the applicability of electric motive power thereto in comparison with steam. It is necessary to pick out a concrete case and estimate all the features in detail, just as it is in order to properly gauge the economic value of any other engineering enterprise. It is obviously unscientific to advocate wholesale electrification as a means of increasing capacity, when the capacity can be increased more cheaply, as it sometimes can, by the introduction of a block-signal system, or when the capacity of a piece of road even when equipped with a block-signal system, could not be increased in practical operation to a point that would enable enough more ton-miles per day to be run off at a lower cost per ton-mile, to show a saving in total annual cost.

The writer is a firm believer in the value of electric motive power as a means of increasing a railroad's earning capacity, but begs to suggest that in the future more professional papers be devoted toward giving concrete illustrations in a manner that will carry some conviction to the minds of the progressive and highly trained specialists in transportation, who are doubtless willing to be convinced if the subject can be dealt with in a manner that appeals to their practical experience in the operation of trains.

A paper to be presented at the 224th Meeting of the American Institute of Electrical Engineers, New York January 10, 1908.

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A SINGLE-PHASE RAILWAY MOTOR.

BY E. F. ALEXANDERSON.

The various single-phase railway motors which have been developed during the past few years have been styled in general as either repulsion or as series motors.

The characteristics of the compensated series motor are well known; it comprises an armature, an exciting winding, and a compensating winding, usually all connected in series. One of the principle objections to this type of motor is the generation of an electromotive force in the coils of the armature which are short-circuited by brushes at the instant of commutation, due to the alternating character of the field. On this account this motor is limited to use on low terminal voltages.

The repulsion motor (invented by Elihu Thomson) has a short-circuited armature and a rotating flux. At speeds near synchronism the electromotive force of alternation in the short-circuited coils is counterbalanced by an electromotive force of rotation. The energy is introduced into the stationary winding and the motor can be wound for any desired voltage.

The most prominent types of single-phase railway motors which have found commercial application are:

1. The compensated repulsion motor (Latour-Winter-Eichberg). This motor has a short-circuited armature and an extra set of brushes for producing compensation, with a view to obtaining a higher power-factor.
2. The compensated series motor (Eickmeyer-Stanley-Lamme).
3. The compensated series motor with shunt-excited commutating poles (Milch-Richter). In this motor, a commutating field is produced locally by coils in the stator.

The motor to be discussed in this paper is neither a series nor a repulsion motor in the generally accepted sense, but embodies the best features of both. For lack of a better name it may be called a "series repulsion motor". The windings resemble those of a series motor, and the armature and stator are permanently connected in series. A general diagram of the motor is shown in Fig. 1. The terminal voltage of the series repulsion motor can be selected with greater liberty than in a series motor, but not so arbitrarily as in the case of a repulsion motor.

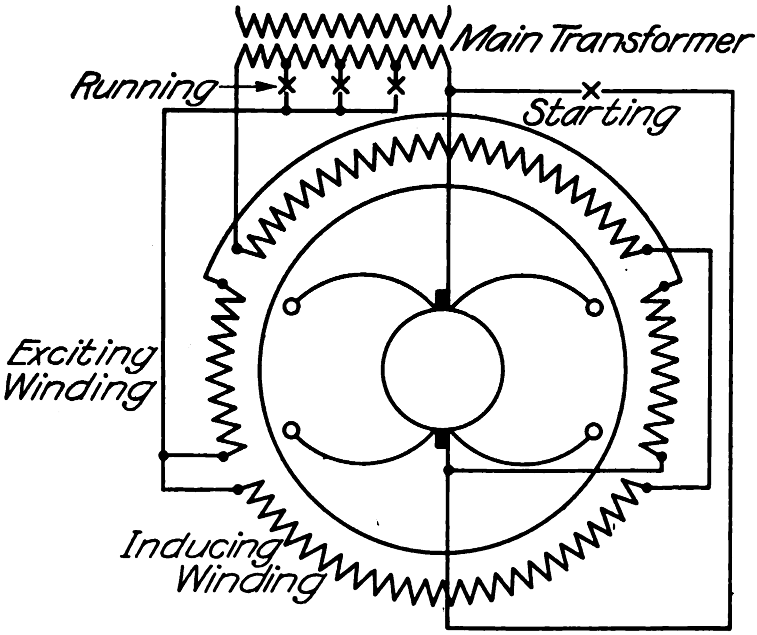

Fig. 1

Its advantages over the straight compensated series motor are very marked. The commutation is so radically improved that resistance leads are unnecessary and it is feasible to build the motors in larger capacities.

In its performance it resembles the series motors with commutating poles, but offers several distinct advantages over the same. Instead of producing a commutating flux locally by coils on the stator, the conductors in the armature are located in such places where the desired flux will naturally exist. This arrangement simplifies the stator winding considerably. The compensating winding of the series motor is replaced by an inducing winding with twice as many turns, and the energy is introduced either in the stator alone or in the stator and rotor together. By this arrangement, as will be explained later, the starting torque is doubled for the same commutation and the same supply of current.

In the compensated repulsion motor the commutating field becomes too strong as soon as the speed appreciably exceeds synchronism, unless special arrangements are made to suppress this field locally. The motor under consideration is not limited by the synchronous speed, as the repulsion motor feature is reduced at the high speeds, and its action follows more closely the performance of a series motor; the number of poles can therefore be selected with the same liberty as in a series motor. This is of great importance for the motor characteristics, particularly in regard to weight and starting torque. Furthermore, no extra set of brushes, nor any series transformer, is required, which makes the motor equally well adapted for direct and alternating current. These being the most important general characteristics of the motor, there are a number of features which are of interest, particularly to the designer. Before entering into these details it will be necessary to give the general theory of the repulsion motor, together with the general theory of commutation.

The pure repulsion motor has a rotating field, and it appears plausible that commutation may be good in a rotating field, provided that the armature rotates at approximately the same speed as the field. However, a rotating field is not in itself a guarantee of good commutation.

When the field becomes ellipitical in shape, it is difficult to grasp the phenomena of commutation unless the field is resolved into its components and expressed as functions of time and space. If this is done, the following field components influence the commutation, as illustrated in Fig. 2.

A. The "main field", which is the torque-producing field, and corresponds to the field in a series motor.

B. The cross-field magnetized by an exciting current flowing in the armature, and serving to transfer the energy from rotor to stator. This field is in quadrature with the main field in time as well as space.

C. Another cross-field magnetized by the difference between the ampere-turns of the armature and the inducing winding. This field is in phase with the main field.

D. The leakage flux around the commutated coils.

The conditions for perfect commutation are as follows:

1. The electromotive force of alternation of the main field should be neutralized by the electromotive force of rotation in the cross-field designated " B ".

2. The magnetomotive force of the stator should be larger than the armature reaction; the difference, which is the field designated " C ", should be large enough to overcome the voltage due to the leakage flux.

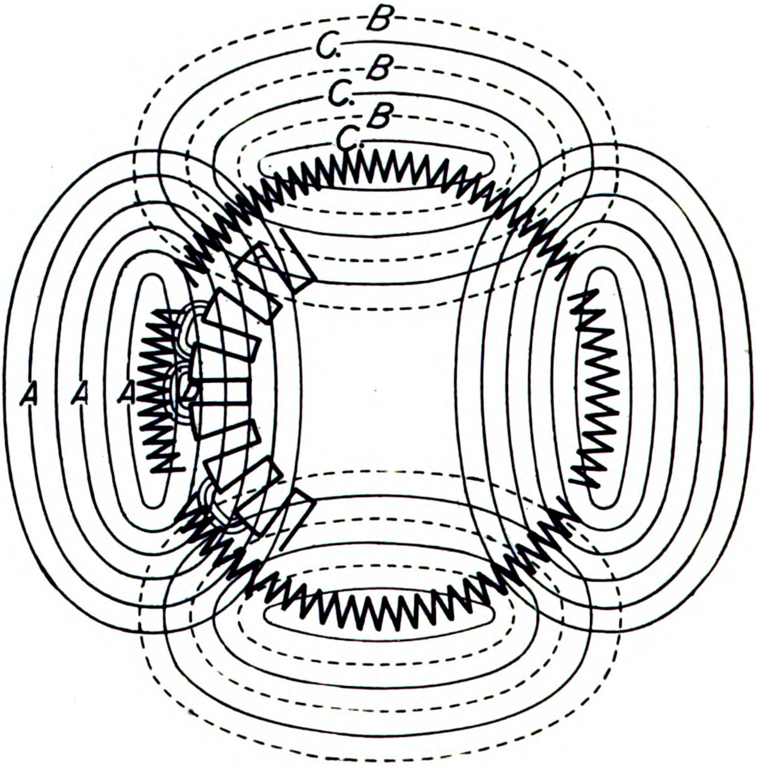

Fig. 2

If these conditions are fulfilled, the commutation is identical with that of a direct-current motor with commutating poles.

The first condition is found at synchronous speed in a repulsion motor, and theoretically in a series motor at infinite speed.

In a series repulsion motor it can be obtained at any speed by varying the proportion between series and repulsion motor action.*

This, however, meets only one of the fundamental conditions necessary for good commutation; there are others which will affect commutation as much as will shifting the brushes of a direct-current motor from the right to the wrong side of the neutral.

The type of motor which is generally referred to as a repulsion motor is that with a continuous stator and rotor winding, and the brushes shifted in the direction of rotation as in Fig. 3.

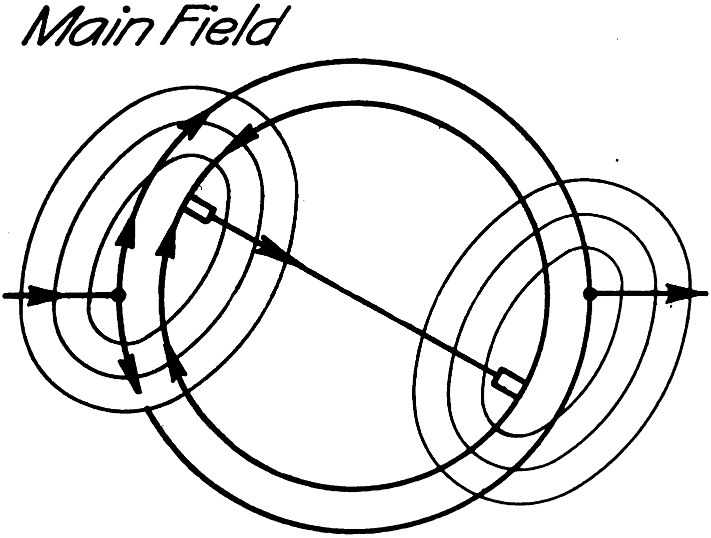

Fig. 3

If such a motor is used as a series motor with the stator and rotor connected in series, it is apparent from the diagram shown in Fig. 4 that that part of the windings which is included in the angle represented by the shift of the brushes constitutes the exciting coils, and the lines of force are distributed as shown on the diagram. The brushes are shifted in the direction of rotation and are located on the edge of the active field. It is well known in direct-current practice that the brushes of a motor ought to have a backward shift, if any, but never a forward shift; and it is therefore obvious, considering the direct-current features, that this motor cannot commutate well. In the repulsion motor, the armature currents are induced by the transformer action, but the distribution of the currents is substantially the same as described above for the series motor. This difficulty has led to the design of an armature winding as shown on Fig. 5, by which the electromotive force due to the cutting of the active flux is eliminated. The magnetization is produced by a separate stator winding located symmetrically with respect to the brushes. This gives a distribution of the fields as shown in Fig. 5. The armature conductors under commutation are located on the edge of the field flux, so that both sides of the coil are under an equal flux of the same polarity.

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* Diagrams have been shown by Milch & Latour with a voltage impressed on the armature circuit in order to meet this condition.

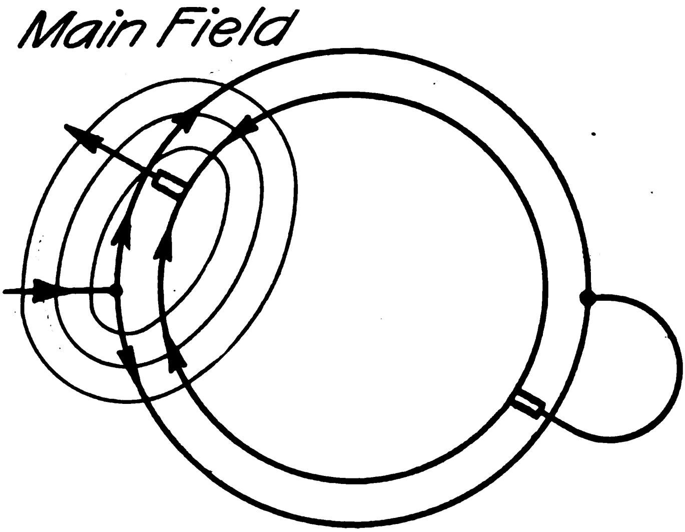


Fig. 4

There is another way of looking at this phenomenon which leads to the same result: the winding of the repulsion motor can be separated into an exciting winding and an inducing winding; in this case the brushes are located in the neutral of the stator winding. The armature is the short-circuited secondary of the inducing winding and must consequently have substantially the same total number of ampere-turns. The two fields that are excited by the stator and rotor individually are shown in Fig. 6 (*a*). The rotor field is peaked and stator field is flat-topped, giving a resulting field as shown by the cross-section part of the diagram. Consequently, there is a resulting peaked field opposite to the brushes where the conductors under commutation are located. This field is excited by the armature and has all the detrimental effects of armature reaction. Fig. 6 (*b*) shows how this is overcome by a fractional pitch winding on the armature. It also shows why only one definite winding pitch gives the correct result, whereas a greater or less ratio gives a field in the wrong direction.

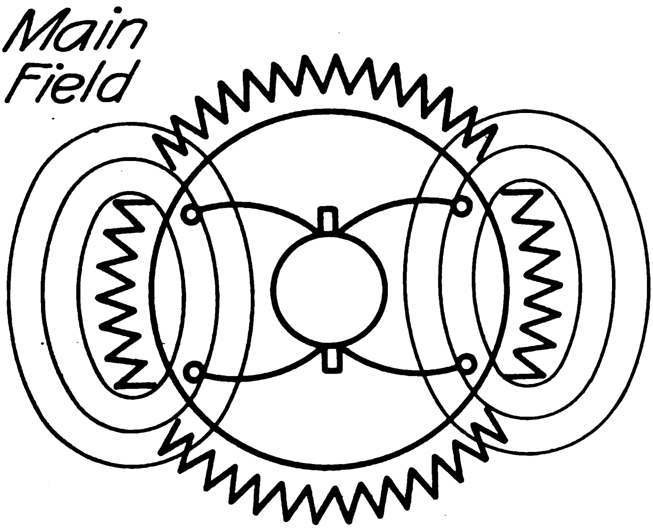
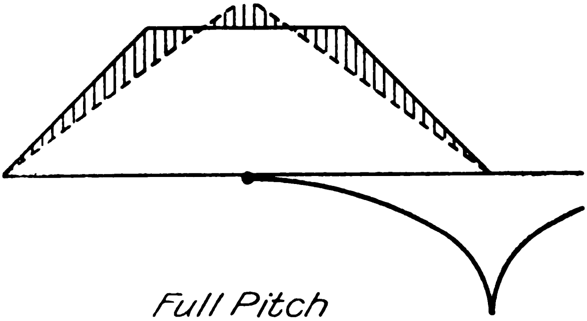


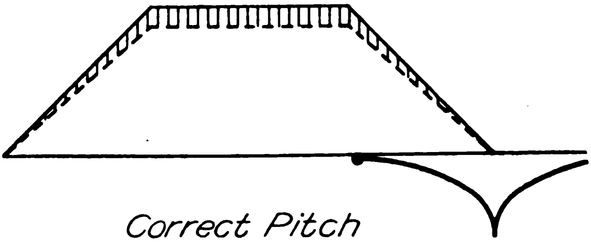
Fig. 5

The correct combination in Fig. 6 (*b*) shows the rotor flux slightly lower than the stator flux, whereas if there were no leakage the currents and corresponding fluxes would be equal; but actually, the primary is a little higher due to the leakage. The difference between these two fluxes acts as a commutating field; but, on the other hand, the higher the leakage, the higher will be the commutating flux needed to overcome the leakage.



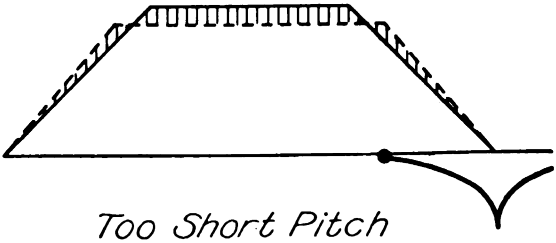
Full Pitch

Fig. 6a



Correct Pitch

Fig. 6b



Too Short Pitch

Fig. 6c

If, however, the armature is short-circuited through a reactive coil, the resulting flux is increased without introducing leakage in the armature. Since the field of the motor is a reactive coil itself that must be excited, a convenient way of introducing reactance into the motor armature is to use the motor field or a part thereof for this purpose. That it is beneficial for the commutation of a repulsion motor to introduce the field in the armature instead of the stator circuit was experimentally demonstrated long ago by E. W. Rice, Jr. The reason for the improvement as explained above, is that the reactance of the field changes the ratio between stator and rotor ampere-turns so as substantially to offset the wrong distribution of currents with the full-pitched winding. The fact of the reactive coil being the field winding is in this respect immaterial, and it has been proved that the field of a similar machine introduced in the same place gives the same result.

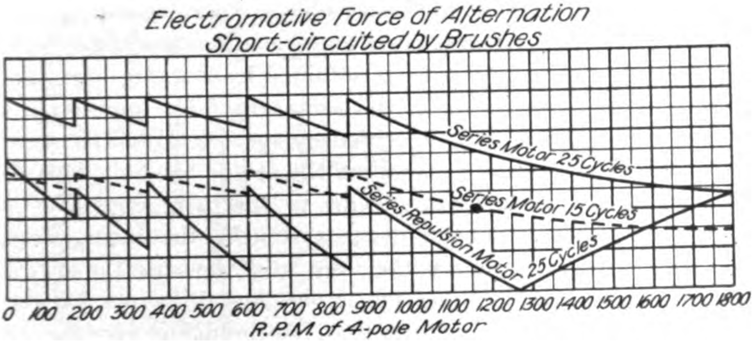


Fig. 7

The above discussion demonstrates how the two fundamental conditions for good commutation can be fulfilled in a series repulsion motor at any speed without the aid of commutating poles. Instead of creating a commutating flux artificially in a place where the commutated conductors happen to be, the conductors are located in a place where the correct flux will naturally exist. By controlling the value as well as the phase of the different fluxes as described, perfect commutation can be obtained at any speed.

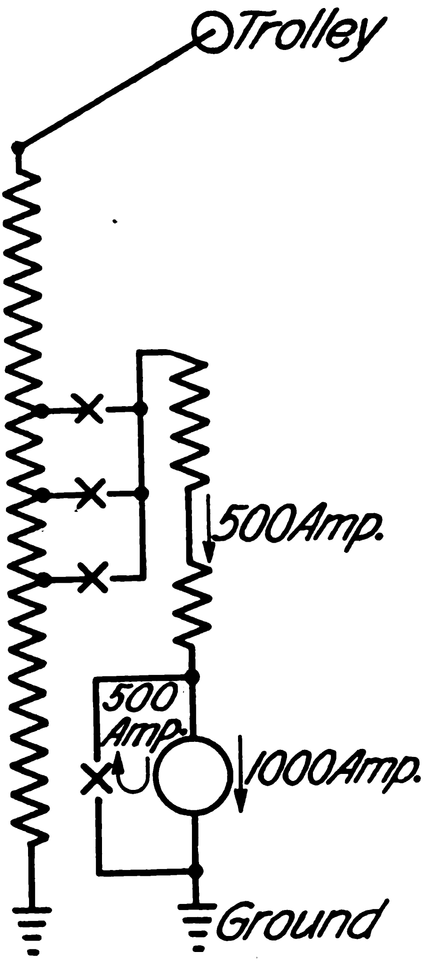
Fig. 7 gives a comparative diagram of the alternating voltages in the short-circuited coils of a series repulsion motor for 25 cycles and for the same motor when used as a series motor for 15 and 25 cycles. The improvement introduced by the fractional-pitch armature winding is a separate matter and is of the same character as the change from an ordinary direct-current machine to a commutating-pole machine.

STARTING

The starting of a single-phase motor is materially handicapped by the fact that the alternating nature of the main field sets up currents in the armature coils which are short-circuited by the brushes. This same difficulty is experienced in all known types of single-phase commutator motors. Although the principle involved is the same in the motor under consideration, the practical result gained by the arrangement employed is a starting torque twice as high as would be possible in a corresponding series motor for the same commutation and the same supply of current.

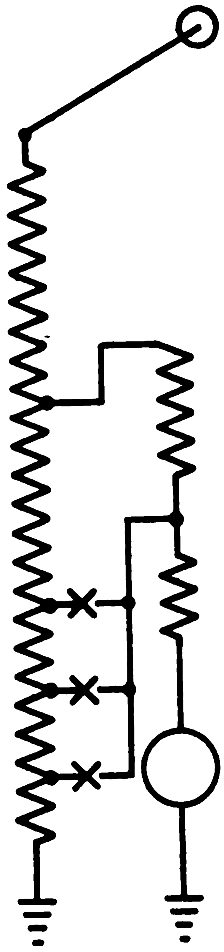
This double starting torque is obtained by winding the stator with twice as many turns as the armature. The motor starts as a repulsion motor with the armature short-circuited as shown in Fig. 8. The current as it enters the stator has only half the strength of that in the rotor, owing to the ratio of stator to rotor turns. The short-circuiting switch of the rotor carries only half as much current as the rotor itself, because the current in the short-circuited connection is only the difference between the stator and the rotor current. The inducing winding, the field, and the armature are connected permanently in series; but with the connections shown, the field is in series with the stator circuit at starting and with the rotor circuit when running. In starting, the rotor carries twice as much current as when running, in order to give the same field strength—in this manner doubling the starting torque. The sparking at starting is quite insignificant up to a certain value of the voltage short-circuited by a brush, but beyond this point the commutation rapidly becomes bad. This critical value is about the same as that which gives a reasonably good commutation in running. For a pure compensated series motor, therefore, the same remedy must be looked for in running as in starting conditions, and the natural solution is to design the motor for a low voltage or to use resistance leads.

In ordinary series motor equipments, the difficulty arises that a higher starting torque is usually required than the full-load running torque, and if the short-circuited voltage is permissible in running, it will get too high at starting. A starting torque of twice full load (one-hour rating) torque is, however, usually more than enough, and therefore the short-circuited voltages can be kept below the critical point, while the torque is increased above normal. It is, however, not only the critical value of the voltage, but also the time that such a voltage is maintained



Starting

Fig. 8



Running

Fig. 9

that determines what is permissible. In this respect any repulsion motor has a great advantage, because the sparking disappears altogether as soon as the armature has reached an appreciable speed. Furthermore, a voltage could be allowed in starting with double torque which would not be permissible with normal running torque, on account of the short time-element of the starting condition.

The general principle which has been discussed for regulating the field in starting an alternating-current motor can be applied in different ways; it was first employed by Eichberg, who used a variable series transformer in the field circuit. Particular attention may, however, be called to the simplicity of the arrangement described here, where the same result is acccomplished through the inherent characteristics of the motor without the use of any additional apparatus. The same principle can be appplied to series motors by the use of a series transformer or some suitable controlling device, but it involves the disadvantage of doubling the current which is to be supplied to the motor through the control system, whereas when starting as a repulsion motor, increased torque is gained by a local current superimposed on the main current by induction.

Control. In regard to the practical application of the system, it may be mentioned that several four-motor equipments for alternating and direct current have been in operation for some time. The alternating-current control equipment has a total of seven contactors and a reversing switch. This gives four points on the controller which seems quite satisfactory for motor-car operation, though any number of steps can be added to take care of locomotive operating conditions.

The preferred method of control is the one shown in Figs. 8 and 9. In starting, the armature is short-circuited and the full secondary voltage of the transformer is impressed upon the inducing and exciting windings. The current flowing through the stator continues through the armature, but due to the ratio of turns of inducing winding and armature winding, an additional current of equal strength to the stator current flows through the local circuit of the armature and the short-circuited connection. In the running connection, part of the power is introduced in the stator and part in the rotor, and the field winding carries the same current as the armature; that is, twice the stator current, thus giving a relatively greater field strength than in the starting condition, just as it would be produced by a series-multiple connection of the field winding.

Although the total potential impressed upon the stator and rotor is the same for starting and running, the result of changing the connection so as to transfer the energy input from the stator to the rotor has the effect of increasing the resulting voltage of the motor. This is due to the ratio of transformation between stator and rotor. In this manner a higher speed is obtained by impressing a higher resulting voltage, and the same change of connections makes the motor adapted for a higher speed by changing the ratio of series and repulsion motor action.

Power-factor. The only motor that has an inherent claim on unity power-factor is the direct-current motor. In every alternating-current motor a certain amount of wattless volt-amperes is consumed in magnetizing the field, and in leakage, so that the maximum torque is limited to a lower value than it is with the direct-current motors. An alternating-current motor with inherently good power-factor is one with high overload capacity, and this must be due to a comparatively small proportion of volt-amperes being consumed for magnetization. There are, however, artificial methods of bringing the power-factor of the alternating-current motor up to unity. For example, an induction motor can be shunted by a condenser, and a commutator motor can be arranged so as to generate a certain amount of volt-amperes in order to supply its own magnetization. Any arrangement for this purpose does not improve the torque characteristics of the motor, any more than a condenser improves the performance of the induction motor; it improves only the phase displacement of the supplied current. The effect on the system can be corrected equally well by other machines on the same system adjusted for leading current.

The alternating-current series motor has a higher power-factor than the three-phase induction motor with the same magnetic structure, because the series motor generates a certain amount of volt-amperes. The power-factor of a series alternating-current motor can be increased to unity by displacing the phase of the field current; for instance, by shunting the field with a non-inductive resistance. In fact, the higher power-factor is due to internal shunt currents, the core-loss as well as the short-circuit current in the brushes having the character of shunts on the field winding. Eliminating the core-loss as well as the short-circuit currents in the brushes would, therefore, evidently improve the motor itself, although it would lower the power-factor.

The following is a short statement of the functions of the different fluxes in a repulsion motor. The motor is understood to be designed, as described before, with a definite degree of fractional pitch and the brushes in the neutral position.

Power-factor of the repulsion motor with field winding in stator circuit. In a repulsion motor, the current passing through the inducing winding produces a corresponding current in the armature. By the rotation of the armature in the main field, an electromotive force is generated in the armature, which causes a magnetizing current to flow which is superimposed upon the main current, and it is this magnetizing current that caused the voltage to be transformed back to the primary. In other words, the current is transformed from the stator to the rotor and the electromotive force generated in the rotor is transformed back to the stator. One flux is needed to transform current and another flux to transform the voltage. These two fluxes are out of phase. The voltage flux is generated in the armature by rotation and does not consume any volt-amperes from the line. The main flux as well as the current flux and the leakage flux consume volt-amperes.

Power-factor of the repulsion motor with field in armature circuit. The theory of this motor is the same as above, except that it takes more flux to transform the current because the armature circuit includes the impedance of the field. Why this increased flux is good for the commutation has been shown above. The same magnetizing current for the voltage flux as described above flows through the armature, and in this case through the field also. This magnetizing current displaces the phase of the main field, and consequently the electromotive force of the machine. The displacement tends to lower the power-factor and the result is the same as if the volt-amperes of the voltage flux had been supplied from the line. In other words, the motor has the same inherent power-factor as a single-phase induction motor.

A series repulsion motor as developed for railway service has only one-third to one-quarter repulsion motor action, this being the proportion that gives sparkless commutation from synchronous to double synchronous speed. The lowering of the power-factor due to magnetizing current is therefore very slight, and with the greater liberty in design that is gained in the series repulsion motor, the power-factor is practically the same as in a series motor.

The analysis of the phase displacement also indicates how the power-factor can be corrected by shifting back the phase of the field current. This can be done in the series repulsion motor as well as in the series motor by shunting the field by a resistance according to the suggestion of Mr. A. S. McAllister. It can also be done, as has been experimentally demonstrated, by a slight degree of separate excitation of the field derived from the main transformer or from the stator coils. However, any raising or lowering of the power-factor of phase displacement does not affect the tractive effort or heating of the motor; it only changes the voltage that has to be applied in order to overcome the inductive drop. As soon as any artificial method of raising the power-factor involves any complication, for instance, another set of brushes on the commutator, it will probably prove preferable to improve the constants of the system by using synchronous machines wherever power is used for other purposes.

Resistance leads. The use of resistance leads, which has been so much discussed, has been found to be unnecessary in motors of the type described. Certain motors which have been operated for a considerable time as series motors, and then rewound so as to embody the features described in this paper, have shown an increased life of brushes and commutator up to the standard of good direct-current practice. The improvement in commutation was so great that it was possible at the same time to increase the thickness of the brush and the output of the motor.

Selection of frequency. In regard to choice of frequency, the series repulsion motor again gives greater liberty. Whereas the starting torque can be doubled on either 15 or 25 cycles, it may be mentioned that a series motor which was almost inoperative at a certain load at 25 cycles, after rewinding, as described, was tested as a series repulsion motor, and found to give excellent commutation at 40 cycles, at the same load. It can therefore be said in general that 25 cycles is entirely satisfactory for all geared motor work; it is preferable in that the combination of motor and transformer weighs less at 25 than at 15 cycles.

A general discussion of the selection of frequency really falls outside the scope of this paper, as the motor referred to is equally well applicable to 15 or 25 cycles. It is, however, the impression of the author that the only argument that remains for 15 cycles is the direct-connected motor for high-speed passenger locomotives. It is, therefore, a question whether the policy of the railroads in regard to frequency should favor 15 cycles because of the requirements of the design of a particular type of locomotive with a limited use, when the freight work as well as the multiple-unit motor trains can be handled more economically at 25 cycles.

Economy of material. The motor described can be built in larger capacities than the series motor. The principal reason for this is the inherently good commutation and increased starting torque which make resistance leads unnecessary, thereby eliminating the heat generated by the resistance leads, and also gaining space in the slots, which can be used for copper. Furthermore, it is possible to increase the flux per pole without impairing the commutation.

The fractional pitch winding which is used primarily for the sake of commutation is also advantageous from the point of view of economy of material. The saving extends not only to the end-connections, as is the case with the fractional-pitch induction motors, but also to the stator winding, inasmuch as only the active armature conductors, or only about 80% of the total, need to be compensated for; whereas with the full-pitch armature, the entire winding must be compensated for. In neither case is it possible to utilize more than about 80% of the total pitch as effective pole arc, because of the space occupied by the field winding. This principle is applicable to any type of compensated machine of the Deri type for alternating or direct current, except when the commutating pole is used.

The fact that the number of poles in the series-repulsion motor can be selected without regard to the synchronous speed is an important consideration. The tractive effort of an alternating-current motor referred to the periphery of the armature is directly proportional to the number of poles employed, provided that the same flux per pole is used and the same current density in amperes per inch of circumference. The allowable flux per pole depends upon the type of winding and thickness of brush, but the same limitations exist for all known types of motors. The formula for tractive effort given below is deduced from the fundamental formulas for commutator machines, but it is of special interest because it brings all motors to the same basis and shows the advantage of liberty in selecting the number of poles.

The tractive effort in kilograms at armature periphery =

$$\text{amperes per cm.} \times \frac{\text{flux}}{\sqrt{2}} \times \text{number of poles} \times \frac{1}{9.8}$$

The only constant in this formula is the acceleration of gravity, 9.8, in the metric system.

Tractive effort in pounds at armature periphery =

$$\text{amperes per inch} \times \frac{\text{flux}}{\sqrt{2}} \times \text{poles} \times 0.089$$

This formula also indicates which method can be considered to obtain as high a starting torque as possible with a given number of poles. The starting torque depends only upon the flux per pole and the current-density. The permissible flux can be slightly increased by use of resistance leads. A considerably larger increase can, however, be obtained by raising the current density momentarily without changing the flux. This is the method that has been adopted in the motor described.

At first glance it may appear that this method would lead to an overheating of the winding. This, however, is not the case. In a motor of this type the I^2R losses are of about the same magnitude as the losses due to the field and the rotation. The total losses of the motor are therefore not increased by the square of the current, but more nearly in proportion to the current. Furthermore, when an increased starting torque and increased acceleration are obtained by increased current, the duration of the excessive current will be so much shorter, with the result that a train can be brought up to a certain speed with only slightly higher heating if this is done at a higher rate of acceleration and with the use of an increased current.

In summing up the preceding the particular advantage of the motor described may be claimed to be:

1. Good commutation at all speeds without the use of resistance leads.
2. Larger capacities possible than with the series motor.
3. High tractive effort possible, due to the liberty of selecting the number of poles.
4. Increased starting torque, possible because of the inherent ratio of winding turns, without supplying an increased current from the main transformer.
5. Simplicity of construction. The stator is the same as in the series motor, in fact easier to construct due to the greater liberty of placing the field-winding in slots. The armature is constructed according to standard direct-current practice with the conductors soldered into the commutator bars.
6. Equally well applicable to direct and alternating current.

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THE NEW HAVEN SYSTEM OF SINGLE-PHASE DISTRIBUTION WITH SPECIAL REFERENCE TO SECTIONALIZATION.

BY W. S. MURRAY.

The method and distance chosen for sectionalizing the high-tension wires supplying power for alternating-current traction is worthy of careful consideration. Local conditions play so important a part in the correct conclusion of method and proper distance to be applied, that no precedent or convention can be followed and standardization is quite out of the question.

In advance of taking up the concrete subject at hand, doubtless it will be of interest to touch upon several alternative distributing systems that were considered by the engineers of the New Haven road before the final adoption of the system of single-phase distribution and sectionalization now in service. Some of these were:

1. 11,000-volt, three-phase generation at the power house; transmission along the right-of-way at this voltage; step-down transformers furnishing trolley voltage at 3300; track mileage divided into three equal linear parts, each part being supplied by an individual phase.

2. The same arrangement as (1) with the exception that step-down transformers furnish 6600 volts to trolley.

3. 11,000-volt, three-phase generation at power house; transmission along the right-of-way at this voltage; track mileage divided into two equal linear parts, each part having its trolley connected through the transmission line to one of the three terminals of the power-house bus-bars, the remaining

bus-bar being connected to the tracks, thus making a common connection for the two trolley sections.

Diagrams 1, 2, and 3, Fig. 1, represent in the simplest form the three above described arrangements. It follows, of course, that the phased divisions in each case could be further individually subdivided into sections wherever desirable. The presentation of these three methods of distribution by no means prescribes the limit of combinations that may exist, as many others of an interesting character have been suggested.

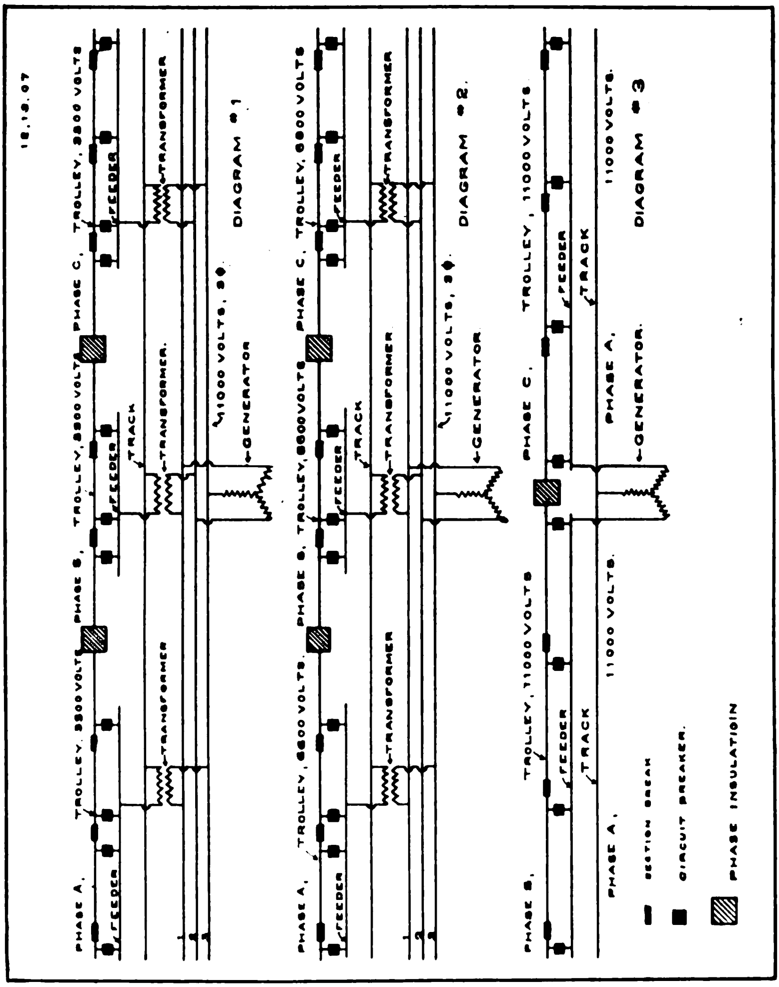

FIG. 1

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4. 11,000 volt, three-phase generation, transmission along the right-of-way at this voltage, only one phase being applied to all sectionalized trolley wires throughout the zone of electrification. The three phases are also carried throughout the electrification zone, and are at all points available for polyphase motors, such as would be used in railway machine shops and for the operation of motor-driven generators in local direct-current railway plants owned by the railroad company.

In Diagram 4, Fig. 2, there is shown diagramatically the actual scheme of single-phase distribution which has been adopted, and is now in service.

There are advantages to be gained in any one of the above mentioned alternatives, but the single-phase distribution as described under 4 carries with it advantages, the sum of which far outweighs the sum of the advantages in the others. In a word, the distribution, as described under 1, 2, and 3, would seem to offer a better opportunity to distribute the load in the three-phase windings of the generators, and yet this is open to question on account of the possible unequal distribution of trains in the individual phased sections; but the greatest and deciding disadvantage to any of the three-phase distribution schemes is the complication that results in the overhead system, together with the fact that for an equal weight of overhead copper the efficiency of the single-phase system is higher than any of the polyphase arrangements. From the foregoing, I believe it will be generally conceded that the single-phase scheme of distribution is the best.

A modification of arrangement 4, which was considered, may be mentioned; namely, 11,000-volt, three-phase generation, single-phase distribution for traction with step-down transformers distributed along the line, their secondaries furnishing 3300 or 6600 volts to the sectionalized trolleys. For the reason that the life-hazard in using 11,000 volts was not considered to be greatly increased over that of 3300 or 6600 volts, and in view of the higher efficiency, lesser currents to be collected by locomotive shoe contacts, greater reliability, and the lower operating costs (no transformer sub-stations) the advantages of the 11,000-volt direct transmission to the sectionalized trolleys was immediately apparent, and the problem became simply one of insulation.

As concerns the choice of three-phase generators in connection with single-phase distribution for traction purposes, again local conditions were the real factors that framed this conclusion. Single-phase or balanced polyphase voltages are undeniably more desirable than unbalanced ones; at the same time when proper allowance and arrangement are made for the unbalanced voltages, and there is a decided market for polyphase power, it is difficult to escape the conclusion that it is a desirable and necessary adjunct. to the system. In connection with its application to the New Haven electrification, it may be said that synchronous motors will be shortly substituted for steam engines in one of our lighting plants. Such arrangements will bring about the centralization of power generation, and by proper field adjustment of the synchronous motors the general power-factor of the single-phase system will be raised.

Having touched upon some of the determining factors that brought about the arrangement of three-phase generation and single phase distribution, the remainder of this paper will be confined to a discussion of the methods and lengths involved in the sectionalizing of the single-phase distribution, and as the power wire (which is the outside wire marked *P* in Fig. 4) plays only an unimportant part in its applications to the traction system, it will not be referred to again.

An examination of the electrical connections made in and on the power-house, line, and locomotives would bring out the strong similarity of the New Haven System to the well standardized direct-current, (not alternating-current–direct-current) system. Indeed, I think it can be fairly said that the current in either case has the same path to follow, the only differences lie in the nature of the current (alternating and direct) and the voltage. In either case the path is from one bus-bar of the station to the feeder and trolley, thence to the locomotive and from there to the rail and return to the other station busbar. In the alternating-current system is noted, of course, methods of installation common to high-tension practice.

Single-phase distribution offers an excellent opportunity for sectionalizing. As may be seen in Diagram 4, Fig. 2, the system consists simply of the track trolleys, two auxiliary wires immediately adjacent, and the necessary switching complement. Although these auxiliary wires have been called feeder wires and while, as a matter of fact, they do serve to increase the capacity of the overhead system, this is not their principal function, as the amount of copper included in the trolleys would suffice to be within the economic figures of copper loss. The auxiliary wires are installed to serve as by-passes, in the event of it being desired to cut dead any or all of the trolley wires in any section. Thus by this system of auxiliary by-passes any degree of sectionalizing can be used, and any or all trolley voltages in sections can be removed without interrupting the continuity of the voltages throughout the zone.

The lengths of sections are governed entirely by local conditions. No two sections of the 14 that exist in the 21 miles of New Haven electrification are the same. It is seen, however, from these figures that the average length of sections is 1.68 miles, that none of these is over 2.19 miles or less than 1.07 miles.

The best reason that can be assigned for the use of sections is in order that line troubles may be localized. There are many others, and some of a most important character. Indeed, it may be said that were the line absolutely immune from trouble, such as grounding, mechanical failures, etc., there would still be many good reasons for sectionalizing it, and these reasons will develop as the subject is further studied.

One of the most attractive features of single-phase distribution is the elimination of sub-stations with their fixed and operating charges, and unlike the alternating-current–direct-current scheme of distribution, where the length of section is settled by the equation of load and copper to meet it, the single-phase system is not bound by these limiting electrical conditions. Line-loss is forgotten in the establishment of a mechanical construction, the amount of copper in which is only a fraction of the amount required for an equivalent loss for the same amount of power transmitted in the alternating-current–direct-current systems. This convenience of transmission with low loss permits sectionalizing *ad libitum* and the local conditions are accorded almost the entire privilege of decision. The advantage of such a relation between operation and distribution was immediately apparent to Mr. E. H. McHenry, Vice-president of the New York, New Haven & Hartford Railroad Company, whose suggestion that the electrical and train signal blocks be made co-terminus was adopted. It will be noted, then, that of the fourteen electrical sections between Woodlawn and Stamford, nine of these are co-terminus with the signal towers. In each of these towers, there is installed a small panel containing the pilot-switches controlling the trolley (and by-pass) circuit-breakers installed on the anchor bridges. Aside from the economical features of this scheme of control, as no operators other than our present signal operators are required, the value of placing the distribution in the hands of this class of men is most important, their constant attention to matters pertaining to the operation of trains bring about the attention which should be accorded to the distribution of current; their thorough understanding of the conditions of traffic on the various tracks permitting the most intelligent handling of electrified and de-electrified trolleys, assuring at once prompt and reliable service in the matter of handling a situation when cross-overs have to be made on electrified tracks, and while repairs are being made on others from which the voltage has been removed. The value of placing the distribution system in the hands of the signal operators may be again illustrated by saying that should an electric train run past a stop-signal set by the operator, or should the operator desire to stop a train in his block he has only to trip the pilot-switch controlling the trolley circuit-breaker, from which the train is drawing its power, and signal the operator in the adjacent tower to do likewise. The individual value of this protective perquisite is an illustration of the use of sectionalizing outside of the question of line troubles.

As before stated, it is impossible to elect some standard distance for sectionalizing the line and then apply it to a steam road undergoing electrification. It is possible to conceive of an entirely new electric line subjected to this hypothetical course of procedure, but even in this extreme case it is difficult to escape the exceptions that could be taken to it; for example, what a strange coincidence it would be to find fifty towns just two miles apart along a railroad's right-of-way. On the other hand, how important each town would be whereat to locate a signal tower with its complement of electrical equipment.

In the discussion of sectionalization it would seem proper, therefore, that instead of specifying the length of sections, to specify the number to be used over a given total distance; their individual length varying in accordance with the local conditions peculiarly related to them. Upon this basis, it will be interesting to enumerate the following advantages and disadvantages peculiar to a choice of a "small number" and a "large number" of sections over a given distance. In this table it should be remembered that usually the items of advantage for the "small number" of sections will be items of disadvantage for the "larger number" and vice-versa. Also it is assumed that the signal towers along the right of way average

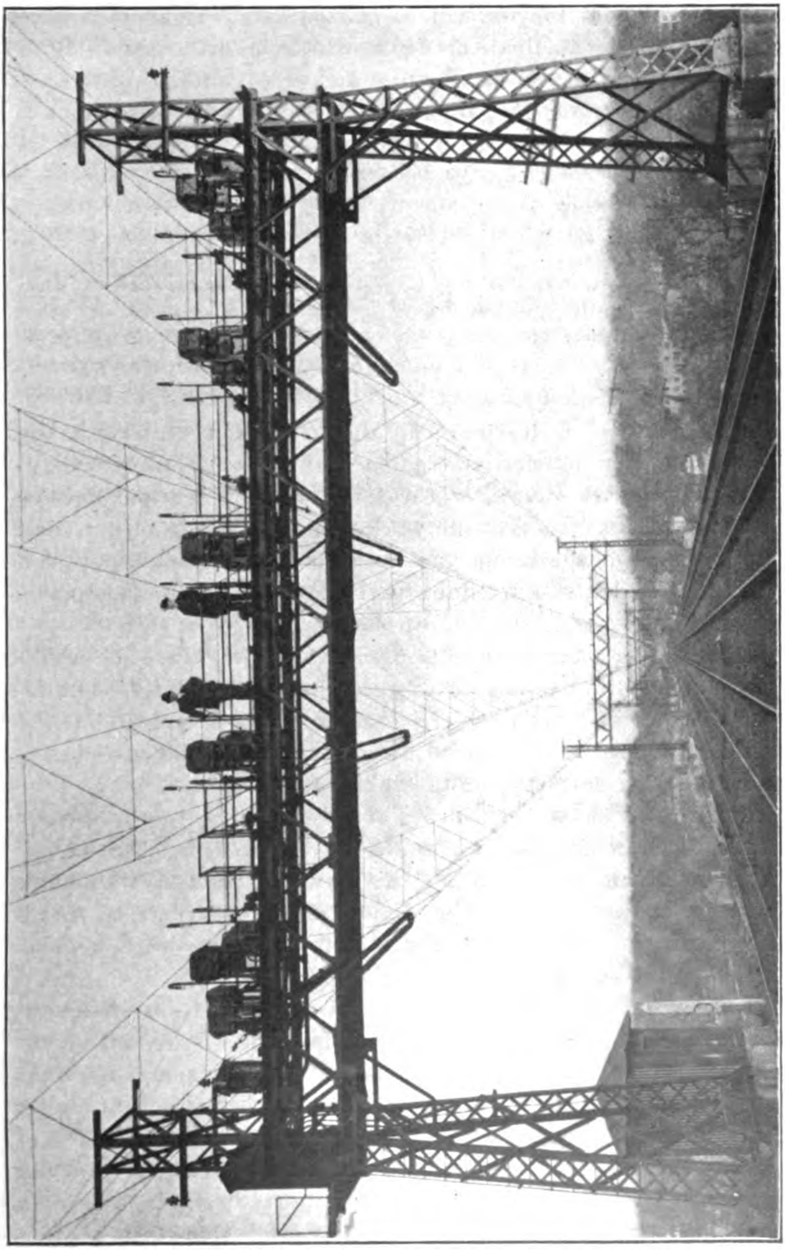

FIG. 3

about one and a-half miles apart and that electrical sections of this length, or longer, will be classed as a " small number " and sections shorter than this will be classed as a "large number."

A tabulation of the advantages and disadvantages of the use of a " small number " against a " large number " of sections is as follows:

SMALL NUMBER

Advantages	*Disadvantages*
1 Co-terminus tower scheme more easily arranged.	1 Difficulty of locating grounds increased.
2 Less switches to maintain.	2 Greater section of track cut dead in case of ground or other trouble. Disadvantage, however, related to cross-overs.
3 More reliable; due to less frequent grounding of line.	3 Larger section breakers required
4 Less cost.	

In advance of a discussion of the items in the above table it is fair to assume that convenience of construction of the apparatus required for either the long or short sections may be equated. That is to say, the work-train service, in either case, would be about the same, and the structures to be put up of a character which would require much the same general superintendence and engineering.

In the case of the long sections, it would, of course, be necessary to splice the messenger cables, as they could hardly be manufactured on single reels greater than two miles in length, but the splicing process would not be a matter of great inconvenience, and would not detract from the value of the cables.

On the other hand, in the case of the shorter sections a greater number of anchor bridges would be required for the supply of sectionalizing switches, but this form of structure would not increase, to any extent, the difficulties of erection, or would the placing of apparatus upon them interfere with regular traffic.

Taking up the discussion of the above tabulation of advantages and disadvantages for the small number of sections versus the larger number; or, stated in another way, sections of greater length versus sections of shorter length, we note that under " advantages."

1. *Co-terminus tower scheme more easily arranged.* In my estimation this is by far the most important factor favoring a small number of sections. It is quite clear that with a great number of sections, their termini would fall at points between towers, necessitating some form of substation or building for

the electrical operators. This would be inconvenient, both for the railroad company and the operator, on account of the cost of maintenance and operation for the former, while the latter would be far removed from his living point.

The reason that the co-terminus scheme is more readily arranged with the use of long sections is apparent, in view of the fact that no convention is necessary to be followed in regard to standard distances, it being at the option of the engineer to choose such towers as are already located on the line as a termini of electrical blocks.

2. *Less switches to maintain.* This advantage is immediately seen, in view of the number of switches being directly proportional to the number of sections, and I believe there is general agreement that a switch in any line does not increase the reliability of that line.

3. *More reliable; due to less frequent grounding of line.* At the present stage of the art, the anchor insulators, which have given the best results from a combined mechanical and electrical strain point of view, have been of corrugated cylindrical form. In this form their insulating value is unquestionably less than the mushroom or petticoat type of insulator, and experience indicates that they are very much less reliable than the mushroom or petticoat type (this form of insulator is used to support the messenger cables on intermediate catenary bridges). It is my belief, however, that by suspending some form of protective shield or petticoat from the anchor insulator, its insulating value will be greatly enhanced. The blast from steam locomotives seems to produce a very rough enamel of coal dust and cinders, which, on account of deeply imbedding itself in the insulator, is almost impossible to remove, in consequence of which insulating values are greatly reduced.

4. *Less cost.* It is immediately apparent that the cost would be much less on account of the elimination of a larger amount of switching apparatus and the heavy bridge work required at all anchorages.

In the table of " Disadvantages " we note:

1. *Difficulty of locating grounds increased.* This is quite apparent, in view of the fact that there are a greater number of insulators between the circuit-breakers, but experience in actual operation has indicated that this is not a serious matter, as the offending insulators are very quickly located, and there is also being perfected at this time a resistance scheme of measure-

ment by which the point of ground can be approximated within 5 % of its actual location; and upon the perfection of this apparatus this difficulty will be eliminated.

2. *Greater section of track cut dead in case of ground or other trouble; disadvantage, however, related to cross-overs.* This trouble would be of a more serious character if it were railroad practice to include a great many cross-overs on the main line. The average distance between cross-overs on the New Haven road is even greater than the distance of the electrical blocks; in consequence of this, should a section become dead on account of a ground, it is possible that the train would have to cross over at a distance from the trouble greater than the length of the electrical section. Railroad engineers look upon cross-overs as a necessary evil (remembering their high cost of maintenance, together with the necessity of interlocking machines in conjunction with them) and it is fair to assume that their distance apart will not be decreased for the convenience of shortening the electrical sections; hence,. this difficulty cannot be classed as one of special moment.

3. *Larger section breakers required.* In the use of longer sections, it is apparent that more trains may be drawing power from the section breakers, in consequence of which it is necessary to design them for greater capacity and they will be called upon to open larger propulsion currents. The difficulty of this, however, fades in the maximum demand upon the breakers being a short circuit, and as this is a duty a section breaker of any capacity has to stand ready to perform, this objection might be considered as not existing.

It would be a strange state of affairs if it were impossible to improve upon any principle or form of construction adopted. In regard to principles which have governed in the electrification and sectionalization as adopted by the New Haven road, I have found by careful inquiry into the opinion of those who are responsible for the operation of our electric trains and the distribution of currents to them, that if any change were to be made, possibly some advantages would accrue in the use of a longer section.

In regard to form of construction. It is fair to say that there are many changes that can be and are being made, which will greatly increase the efficacy of distribution. It is my observation that the New Haven electrification has been looked upon as a radical departure from engineering practice. There is no question about the justice of such a remark when viewing the matter as a whole. If, however, we segregate each link in the chain which forms the whole, I believe it will be found that no one link is a particular departure from a practice that has existed many years. It has simply been the putting together of old principles into a new form. One exception can be made to this statement. The alternating-current railway motor is new, and yet an exposition of its characteristics, such as in its speed and torque curves, show that within it the old underlying principles prevail. Its complements, the powerhouse and line, involve no new principles that have not been tried out under various forms and conditions. A high-tension moving contact has nothing new or of a disturbing nature about it.

When the form of electrification of the New York division came up for decision, there was an easy path of the least resistance open to the engineers of the New Haven road. A form of electrification had been adopted and applied to traffic rails over which the New Haven trains were obliged to go in their entrance to New York City. An acceptance of this form of electrification would have simplified and made easy the duties and responsibility of the engineers of the New Haven road. The right path, however, is not always the easiest, and the principles which existed in their minds were of a character that required a radical departure from the easy and tempting alternative. There is an old saying: "Nothing that is worth while ever came easy," and such has been the case with the New Haven road. We have encountered unexpected difficulties, which are always common to initiative, none of them, however, has been of a character which could be interpreted as a menace to the general principles involved. The difficulties have either been corrected or their correction is easily in sight.

The last six months of operation have offered the opportunity for a collection of valuable data, and the following observations and recommendations are offered in the hope that they may be of some value to other engineers interested in the electrification of steam roads:

1. In one-, two-, three-, or four-track railroads, the single-phase distribution should include besides the trolley wires, by-passes or feeders.

2. Electrical sections should not average less than 1.5 miles in length; greater averages are entirely acceptable and individual lengths should be governed by local conditions.

3. Twenty-two feet is a safe general working distance of trolley from rail.

4. The de-insulating effect of steam locomotives stack discharges is a most important consideration to be kept in mind in the matter of properly insulating high-tension wires from ground.

5. High insulation factors should be used where high-tension construction due to low bridges is brought nearer the rails than the normal height of 22 feet. Strong mechanical shields should be used to deflect locomotive blasts from messenger insulators at low bridges. Care should be exercised in the installation of these shields so that high-tension conductors and ground are at safe working distance. Wherever possible insulators should be installed away from the direct line of the locomotive blast.

6. Auxiliary wires in connection with the electrification, if they cannot be carried over highway bridges as aerial conductors, should not be carried under, unless they are enclosed in lead-covered cables, with end-bells properly enclosed in suitable housings at points where the conductors change from aerial to lead-covered cables.

7. All circuit-breakers connecting feed wires (or by-passes) to the trolley bus-bars should be equipped with time-relays, so that any short-circuit will immediately open the trolley-breakers, thus locating the trolley section grounded. Equipping the feeder breakers with time-relays insures continuity of voltage on wires not affected by the short-circuit. Each trolley-breaker pilot-switch should be provided with a light to indicate when it opens, and an announcer bell should ring in the signal tower at the same time so that the operator is promptly notified.

8. On account of deleterious influences of weather and locomotive stack discharges, together with general inconvenience of getting at bus-bars and switches when installed on anchor bridges, all section oil-switches should be installed in switch houses erected at the side of the tracks, with lead-covered cable connections between trolley and switches.

9. Signaling should be arranged so that the operator can prevent the engineer from spanning two sections by his locomotive shoes in the event of the advance section being grounded.

10. All signal towers should be interconnected with are liable telephone service. Immunity from electromagnetic and electrostatic disturbance in the telephone system can be secured by

using twisted-wire pairs enclosed in lead-covered sheath, the sheath being grounded frequently. This suggestion is more particularly applicable to the interrupted or tower-to-tower telephone system. In this case the distance of exposures of the telephone wires is not great, and thus the summated effect of electromagnetic induction is negligible. In the case of the through telephone line where the circuit is uninterrupted throughout the zone of electrification, again the lead sheath and twisted pair are respectively effective in removing all static charges, and electromagnetically balancing the circuit; but on account of the cumulative action of the electromagnetic induction, either compensating transformers or a system of impedance coils installed across the telephone circuits at intervals of two miles (this distance may be less, depending on the electromagnetic density) with their central points grounded should be used. Either method will satisfactorily remove the impressed voltage due to electromagnetic induction. The importance of reliable telephone service between operating towers cannot be too greatly emphasized.

The above mentioned are some of the fundamental requisites which design and practice have brought out in connection with the New Haven electrification. Design and practice are many times good friends, but if a difference of opinion arises, practice will, in nine times out of ten, have the better of the argument. Experience, the great teacher, has brought out either the efficacy of the original design or the proper modification of it.

The observations and recommendations above cited, are those that have been impressed upon the writer during the period of operation so far attained. Except for certain minor and easily remedied details, experience to date with the New Haven arrangement of single-phase distribution would indicate that the fundamental principles involved have been correctly applied.

A paper to be presented at a special meeting of the American Institute of Electrical Engineers, New York, January 24, 1908.

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(Subject to final revision for the Transactions.)

THE BEST ENGINEERING EDUCATION

AN INTRODUCTION TO A DIGEST OF THE PAPERS ON ENGINEERING EDUCATION IN THE TRANSACTIONS OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, WITH A VIEW TO RENEWED DISCUSSION OF THE POINTS CONTAINED THEREIN

BY CHAS. F. SCOTT

The recent rapid development of the electrical industry owes its vitality to the engineering school. Its graduates have done the designing, constructing, operating, and directing which have made possible the rapid progress and wide extension in the use of electricity. The ideals, the equipment, and the methods in engineering education, as well as the number and size of the schools, show a remarkable rate of progress. In fact, the advance in the electrical industry, in engineering education, and in the American Institute of Electrical Engineers closely correspond when measured numerically. There has been a close interrelation between them.

The future prosperity of the industry and of the Institute depends upon the efficiency of engineering education to an extent which one realizes more fully the closer he studies the subject. It well merits our best thought.

A review of the papers which have been presented to the Institute on engineering education shows that among our modern professors there are those who are active and alert and up-to-date. There is a marked agreement between the teaching profession and the engineering profession, both in an appreciation of the importance of the subject and in the general purposes which the engineering school should aim to accomplish. As engineers, it is quite unnecessary to argue that our schools should be more efficient and that their graduates should be better equipped for the work they are to do, as the professors are urging us to tell them how to accomplish these very objects.

Before discussing how to do something, it would be well to decide what it is we desire to do. What do those who use engineering graduates want them to be able to do? Ideas have varied. Some expect trained artisans; others, trained engineers who are ready at once to do any kind of engineering work. Some expect technical specialists; while others call for men of ability who have a general preparedness for doing any kind of work. Some are disappointed if graduates are not immediately productive; while others provide courses of practical training. As all boys are not alike, and as their future employers have different ideas, and as their jobs will not be the same, it reasonably follows that there is room for more than one kind of training in college. The problem is not wholly abstract; it is vitally concrete. Its solution is not a rigid and narrow one, but it involves general policies. The details of method are to be determined by varying conditions and are to be adapted to the varying personal qualities of the young men.

In general, instruction in engineering schools is of three varieties:

a. Practical or industrial.
b. Scientific,
c. Cultural.

Practical or industrial studies are intended either as illustrations of scientific principles or as a direct preparation for business or professional life.

Scientific studies are the foundation for the applications and make the latter possible.

Cultural studies broaden the student's mental horizon, offset the narrowing effects of technical studies, and prepare for activities which are not purely technical.

The best engineering education is that which fits the individual student for his largest development and usefulness *in the long run,* not necessarily immediately after graduation. The problem, therefore, is to divide the four years spent in school among the three classes of studies in such proportion as will bring about the best results.

The problem is largely one of elimination, as, if all the studies were included which have been suggested as being essential or desirable in the training of an engineering student, the college period of 4 years would have to be increased to possibly 20 or 30 years.

Among the questions which arise in the discussion are the following:

1. The desirable characteristics of the acceptable graduate with respect to:

a. Practical familiarity with electrical apparatus which will enable him to be immediately useful, versus a less practical and more general training, which is to be supplemented by an apprenticeship course or its equivalent.

b. Specialized technical training and technical knowledge, versus a broader education aimed to develop intellectual power rather than the acquisition of technical knowledge.

2. The arrangement of subjects and courses which will best produce the desired results. The following questions arise:

a. The relative attention to be given to the practical or industrial, the scientific, and the cultural.

b. The relative proportion between subjects which are valuable for imparting technical knowledge and those affording training in scientific and logical methods.

c. The relation between school instruction and practical work; whether one should precede the other, and if so which one should come first, or whether they should alternate once a day, once a year, or at some other rate.

d. The importance of current engineering practice; of lectures by practising engineers; of discussion of current topics in local meetings of the Institute.

e. The degree of desirable differentiation in courses or methods on account of differences in the characteristics of individual students or in the fields of work they expect to enter.

f. The sequence of subjects—whether the theroetical groundwork should be laid during the first few years and the practical subjects reserved until the latter part of the course, or whether an intermingling of the two in accordance with the concentric method outlined by Professor Karapetoff is to be preferred.

I venture the prediction that the solution which will find most general acceptance will be that which gives to each student the training which fits him for his largest individual development; that for those who are qualified to take an active rather than a passive attitude toward their work the broader education, which emphasizes training rather than knowledge, will be chosen; that a fairly intimate intermingling of college work with practical work will be found to conduce to the efficiency of each, and that the field in which the greatest difference of opinion will be present will be with regard to the proposed concentric method. This system clashes with time-honored educational ideals, but it presents arguments which are so rational that the existing method must assume the defensive.

Those who were present at the Niagara convention will recall that the discussion on the papers of Professors Norris and Karapetoff was one of the most animated during the convention, and that it was brought to a close only on account of lack of time, although it had continued for nearly an hour after the ordinary hour for adjournment. It was the interest in this discussion which led to the appointment of an Educational Committee by the Institute, and which has led to the present summary (prepared by Professor Norris, chairman of the Educational Committee) of the educational papers in our TRANSACTIONS as a basis for the active continued discussion of this important subject.

DIGEST OF INSTITUTE PAPERS ON EDUCATION

1892. ANNUAL CONVENTION, CHICAGO

Robert B. Owens. The first formal paper on engineering education was presented by Professor Owens under the title, "Electrotechnical Education". The value of the manual element is emphasized and attention is called to the departments of mechanic arts which had been attached to the Massachusetts Institute of Technology, the Washington University, and others. A technical school [according to the author] is primarily a place for the preparation of men who expect to earn their living as engineers. It is not a school of general culture nor is it a school of exact science. It is a device to save time, and teaches the application of pure science to industrial purposes. It is also a post-graduate school, and in this respect should rank with schools of law and medicine. Professor Owens at that time advocated the employment of a number of specialists in order that each student might have the opportunity to choose the work for which he is best fitted. While it is expensive to supply such specialists, and the equipment to enable them to carry on their work is costly, on the score of economy no more profitable expenditure of money is possible than for the support of technical schools. Education is not a money-making business, and can never be made to pay for itself.

Professor Owens outlines the elements of a course in technology, basing his recommendations upon the existence of three kinds of electrical engineers—"installing engineers, designing engineers, and engineering scientists".

Dugald C. Jackson. The technical education of the electrical engineer is one that should continue through life. Professor Jackson con-fines himself to a small part of this education, namely, the college education, and in order to be perfectly definite, he first outlines the course at the University of Wisconsin. The underlying principle is to depend on fundamental theories, with a common-sense view to their particular applications, in such a way as to aid in diagnosis, not by the application of a mathematical formula, but by comparing the accumulated experience of the practical world. It is comparatively easy to teach the fundamental theories, hence it is frequently overdone. It is not so easy to educate the judgment of a student in electrical engineering, whose entire knowledge of his future profession is acquired from the electric bells in his father's house, and who may never have examined a dynamo, or storage-battery, until he visited the college laboratory. Professor Jackson deplores the effect of the rigid specialization required in the technical school, and recommends a preparatory arts course when such is possible, and outlines the elements of the technical part of the course. It is interesting to note that in the paper delivered by him 11 years later he has not materially changed his views.

The discussion upon these two papers indicates the real interest taken in the subject at that early date.

1902. ANNUAL CONVENTION, GREAT BARRINGTON

Between the years 1892 and 1902 practically no attention was paid to the subject of technical education.* In the latter year, a session of the annual convention was devoted to this subject.

Chas. P. Steinmetz, in his presidential address, called attention to the fact that all future progress in science and engineering depends upon the young generation, and to insure an unbroken advance it is of preeminent importance for the coming generation to enter the field properly fitted for the work. Here the outlook appears to him by no means entirely encouraging. The proper function of the educational institution is to give the student a thorough understanding of the fundamental principles of electrical engineering and allied sciences, and a good knowledge of the methods of dealing with engineering problems. At present the average college course does not do this. One of the reasons for the inefficiency of the college course is the competition between colleges, quantity having been increased at the expense of quality. Memory is developed at the expense of the reasoning faculty, and the college courses would be improved if one-half or more of the material taught should be dropped from their curricula, and the rest taught so as to be fully understood with reference to general principles and methods.

One objectionable feature of the instruction at most colleges is the "step-by-step" method. One subject is taken up, by application of sufficient time and energy pushed through, and then after the examination it is dropped and another subject is taken up. To understand a subject thoroughly requires several years' familiarity with it, so that the study of any subject which is not kept up during the whole college course might just as well be dropped altogether.

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* A. A. Hammerschlag prepared a paper in December 1898 on the subject of the education of electrical apprentices and foremen. This presented in an excellent manner the importance of properly training a class of men who could never be electrical engineers in the sense of their being technically trained. This paper is not abstracted here, as it is not in line with the general purpose of the resume.

The present method of examination, which consists in expecting a student to answer ten questions or so in a few hours, is faulty. It shows what the student has memorized, but not how far he understands the subject. In electrical engineering, nothing beyond the general principles is needed for success; time spent in memorizing things to be forgotten afterwards is entirely wasted.

Dr. Steinmetz outlines the ideal course in electrical engineering, advising a good foundation in elementary mathematics, with no memorizing of integral formulas which can be looked up in a reference book when required. A thorough knowledge of science, including physics and chemistry, both theoretical and applied, is strongly urged. Electrical laboratory work should be taken up from the start, even before the theory is understood. Design of electrical apparatus is of secondary utility, and rather objectionable, with the exception of some very simple apparatus. Far better is the reverse operation, the analytical investigation of existing apparatus.

Samuel Sheldon called attention to the necessity for uniformity in electrical engineering courses, pointing out the wide difference in practice in various institutions; for example, engineering students at Cornell University spend ten times as much time on shopwork as those in the Massachusetts Institute of Technology. The range in the various subjects in terms of hour units* are in mathematics from 5 to 11; drawing, 3 to 10; physics and chemistry, 7 to 25; English, 0 to 11.3; French and German, 0 to 10; shopwork, 0 to 21; electrical engineering, 9.5 to 23.8; other engineering, 7.7 to 23.2; thesis and elective, 0 to 7.1. He points out that the aims of a liberal education are as follows:

1. To discipline the mind so as to create a power for coördinate thought.
2. To impart a knowledge of facts.
3. To develop a power of expression in language or in action.
4. To discipline emotional sympathy so as to develop an esthetic taste.
5. To discipline the moral faculty.

The curriculum has a twofold purpose. First to assist the student in choosing a calling which will be congenial and suited to his ability, and secondly to develop equally all his faculties. While radically different in purpose from the arts course, the technical course should produce something of the same results. On the other hand, the legitimate ultimate purposes of a technical institution are so utilitarian and different from those of the liberal institutions, that the extensive use of electives on the part of professors, which is so admirably adapted to ordinary college requirements, is detrimental to the best interests of the technical student and is wasteful of his time.

William Esty. At the same convention Professor Esty outlined several ways in which instruction can be made practical as well as scientific. The ideal education for the engineer is a literary and scientific course of a general nature, covering three or four years, followed by a special technical course extending from two to three additional years. The tendency to regard an engineering course as post-graduate professional work is increasing, as is evidenced by the increased number of graduates of humanistic colleges taking engineering studies. Professor Esty's rules for planning a course in electrical engineering are:

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* An hour in this sense is one hour per week per academic year. This equals about 36 actual hours of lecture, recitations, or quiz, or 72 actual hours in the drawing room laboratory or shop.

1. To teach thoroughly those things in college which are fundamental.
2. To devote little time to highly specialized subjects.
3. To introduce the student to those branches of knowledge which in his later life he can acquire only with increasing difficulty, if at all, and
4. To endeavor to cultivate in him the hunger and thirst for more and deeper knowledge, so that he may remain a student throughout life.

H. W. Buck presented his views of the education of the electrical engineer from the standpoint of a technically trained practising engineer. In its present state, electrical engineering is the most scientific of all engineering professions. A man must be to a great extent a physicist, a chemist, and a mathematician, as well as being familiar with machinery and its design, in order to be a worker in the broadest field. The best course of training for an electrical engineer would seem to be a broad course of education in general subjects at the preparatory school, then a college course with general subjects during the first year, followed by those general and theoretical subjects that have a direct bearing upon the practice of the electrical profession. This includes such studies as mathematics, mechanics, physics, chemistry, theoretical electricity and magnetism, and thermodynamics. This study should be supplemented by actual daily practical work with machinery operated by the principles covered by the theory studied, and demonstrating all the phenomena incident to the theory. Mr. Buck advocates practical apprenticeship work subsequent to the completion of the college course. In addition to the theory and practice involved in this training, other elements are necessary for the successful engineer. There are many qualities required in common with other professions; executive ability, business knowledge, presence of mind, ability to handle men, nerve, resourcefulness in handling machinery in times of emergency—all these are necessary for the successful engineer. These elements cannot be acquired in the study of theory and practice alone, for many men who have stood high in their college courses have afterward failed in the practice of their profession because of a lack of some or all of these qualities.

E. B. Raymond. In another paper at the Great Barrington convention Mr. Raymond proposed the dropping from technical courses of all subjects not of a technical nature, such as language, history, literature, and political economy. The time should be spent entirely upon a theoretical and practical course, which will produce broadminded men with intellect, strength, training, and purpose. To this end the professors should be men of force of character, as well as men of intellectual attainment, and the courses at college should be so arranged that recitation rooms and laboratories could be regarded by the students as we look upon our offices. One of the most essential qualifications of the successful engineer is that he shall be filled with the desire for continual study. After graduation is the time for him to get his knowledge of real detail, amplifying the general knowledge obtained in college by practical investigation.

The discussion on the above papers was even more extensive and interesting than that at Chicago, and indicated an increased interest on the part of practising engineers.

1903. ANNUAL CONVENTION, NIAGARA FALLS

At this convention a joint session with the Society for the Promotion of Engineering Education was held. Messrs. J. G. White, Bancroft Gherardi, L. A. Osborne, representing employers of technical graduates, and Professor Dugald C. Jackson presented papers. The consensus of opinion expressed in these papers is that the personality of the technical graduate is of more importance than any information which he may have acquired.

J. G. White. The results of a successful education may be summarized as (*a*) the satisfaction which results from possession; (*b*) the ability to enjoy good society; (*c*) the practical use which may be made of the training; (*d*) the ability properly to know any subject, and (*e*) the higher rank which will be taken as a result of this training.

Technical education should produce *engineers*, not students. It should develop not dreamers, but workers, thoroughly competent in their spheres whether great or small. It is better for the world and for the man that he should be a high-class mechanic or artisan, with a good common-school education, than that he should be nominally an "engineer", having a smattering of many subjects. *The importance of thoroughness is supreme.*

The telephone engineer's work is an example of the severe requirements of engineering practice. A few years ago many of us would have supposed that the problems of the telephone engineer were those of a high-class artisan, but a modern telephone engineer must even know something of architecture, the strength of materials, and other factors entering into modern steel building construction, and be familiar with many other subjects not ordinarily supposed to come within the province of a telephone engineer. Other engineers should likewise have a general knowledge of the sciences and of the broad underlying principles of engineering, based upon a thorough mastery of elementary mathematics and supplemented by some study of languages, history, civics, and other studies of general educational value.

Bancroft Gherardi. Treating the subject from the standpoint of the telephone engineer, Mr. Gherardi lays down the general proposition that an engineer's qualifications are made up of two factors, personality and training. The training of a telephone engineer should not be essentially different from that of other electrical engineers, the training of any engineer properly consisting of such studies as will convince him of the necessity of getting facts, and teaching him the best method of doing so. Further, these studies should train in the interpretation of engineering data and in reasoning from them. Throughout his paper Mr. Gherardi emphasizes the necessity for relating theory and practice, suggesting that while fundamentals should be the most prominent, examples should be drawn from each branch of electrical engineering to which the fundamental principle may apply. In this way the value of the principle will be borne in upon the mind of the student. He will be helped to see theory and practice in the proper perspective, and will be aided in deciding upon the particular branch of engineering for which he is being fitted. The examples will also not be without some practical value in his early professional work. In regard to his experience with technical graduates, Mr. Gherardi states that the training they receive, notwithstanding its imperfections, is of great value to them and to those for whom they work.

L. A. Osborne impresses the facts that the large majority of young technical graduates are not fitted by temperament or training for pure engineering work, and that they regard it only as a stepping stone to business. At the same time the teachers of these men have proceeded on the assumption that they would be ultimately engaged in engineering. He therefore advocates the broadening of courses to the end that the whole body of engineers will enter upon their work with a fuller comprehension of its duties and opportunities. Mr. Osborne contends that shopwork should be taught with a view to training the student in the principles which underlie the tool organism of a shop. He should know more about the functions of tools, the principles of their design, and their relations to each other. While it is true that familiarity in these lines comes largely from experience, the author infers that the schools can have a share in providing it. Works-accounting, the problems of capital and labor, the law of contracts, and other such apparently non-engineering subjects should not be neglected in the engineering curriculum.

Dugald C. Jackson. Professor Jackson calls attention to the fact that since he brought up the subject in 1892, the sentiment regarding college men has entirely changed. These men have become influential in engineering practice. The business of the engineering colleges is to produce, not finished engineers, but young men with a great capacity for becoming engineers. The names attached to the subjects taught are not very important as the results produced by the teaching, namely, the effect produced upon the students, show. The ideal engineer is competent to conceive, organize, and direct extended industrial enterprises of broadly varied character. He must be a keen thinker with an extended knowledge of natural laws, and an instinctive capacity for reasoning from cause to effect. He must also know men and their affairs, business methods, and the affairs of the business world. The ideal course in electrical engineering should include the following underlying training.

1. That fuller training in the construction of the English language which is requisite to clear thinking and clear writing, preferably accompanied by an additional language for added strength.
2. The collateral art of expression in drawing.
3. Mathematics through an appropriate amount of calculus, including the integration and solution of equations involving derivatives, and instruction in the use of co-planar vectors, and perhaps quaternion quantities—all of which should be taught as applied logic with special emphasis laid on interpretating the meaning of equations.

4. The science of chemistry, soundly taught.
5. The science of physics soundly taught, with particular emphasis laid on the elementary mechanics.
6. Applied mechanics.

Mechanics—the philosophy of matter, force, and energy—is the backbone of the electrical engineer's college training.

He also outlined laboratory and practical courses, which should accompany the fundamentals. He deprecated the use of descriptive courses as having a tendency to neutralize the advantage resulting from instruction in fundamentals.

The work in electrical engineering should be divided into :applied electromagnetism, the theory and practice of alternating variable currents, applied electrochemistry, electrometallurgy, and electrical installations.

In analyzing the courses advertised in college catalogues Professor Jackson finds three varieties of instruction. In the first of these, electrical engineering is taught as an illustration of the beauties of nature, rather than of its great underlying laws. The instructors in these courses are out of touch with the industrial world. The second class of instruction is apparently intended to train inexperienced students to assume positions of responsibility and large remuneration. The third variety of instruction approximates the ideals laid out in the paper. In closing, Professor Jackson states that many of the greatest weaknesses in engineering courses are that the heads of colleges or universities do not understand what engineering truly stands for, and they often have no fair conception of the soundness of training that is required for its practice.

1903. SEPTEMBER MEETING

Chas. F. Scott, in his inaugural address as president proposed that universities and technical shcools with educational engineering departments should hold local meetings of the Institute for benefiting both instructors and students by keeping them in touch with recent developments and practice. It is argued that theoretical training in fundamental principles should predominate and that such Institute meetings will enable the student to keep in touch with actual things and give him a more adequate idea of the career for which he is preparing. It will supplement his theoretical training, making it definite and certain, so that he may properly assimilate the instruction he receives. It will show him that the electrical engineer needs much more than mere technical training, and it will tend to make his college work less abstract and more concrete and efficient.

1907. ANNUAL CONVENTION, NIAGARA FALLS

Henry H. Norris. At this convention education was the subject of two papers; one by Professor H. H. Norris, the other by Professor V. Karapetoff. In Professor Norris' paper emphasis was laid upon the elements of personality in the technical students. The elements of success in technical training are:

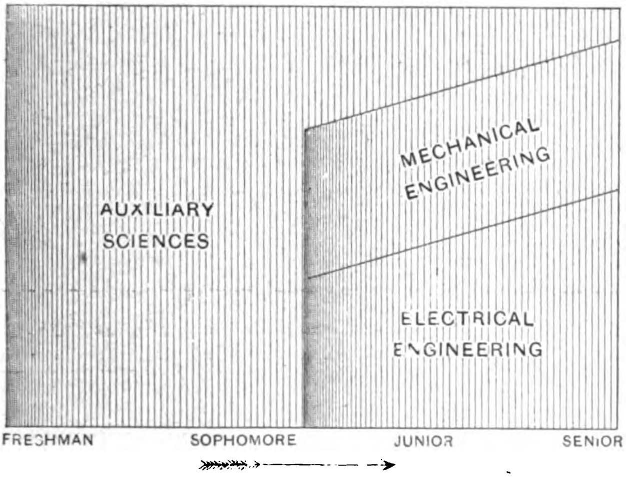
1. The attraction and retention of desirable students and the exclusion of those not qualified for technical work;

2. The selection of such studies as will stimulate and direct mental activity.

3. The conducting of all courses in such ways as will tend to bring out the desirable personal qualities in the students.

4. The recommendation to the students of those lines of engineering practice for which they are best suited.

In developing the subject the author made use of a magnetic analogy of a technical training. The mind of the student was compared to a piece of magnetic material which possesses the ability to be magnetized on account of the inherent magnetism of its molecules. A piece of iron or steel is magnetized when its intrinsic qualities are subjected to a direct magnetomotive force. In a similar manner the young men entering the technical school possess certain elements of personality. The function of the instruction is to supply the directive force necessary to bring out the student's latent qualities. The student gets little that is new from his college course, and if the attempt is made to impart to him more information than is necessary to stimulate him to his best endeavors, mental saturation results. The writer traces the history of the technical school, and refers in some detail to that of Sibley College, which with the Massachusetts Institute of Technology was a pioneer in electrical engineering instruction. The present curriculum of Sibley College was outlined in order to permit it to be compared with the ideals laid down. In order to indicate the lines of work taken up by technical graduates an analysis of the present occupations of the numbers of graduates of Sibley College was given.



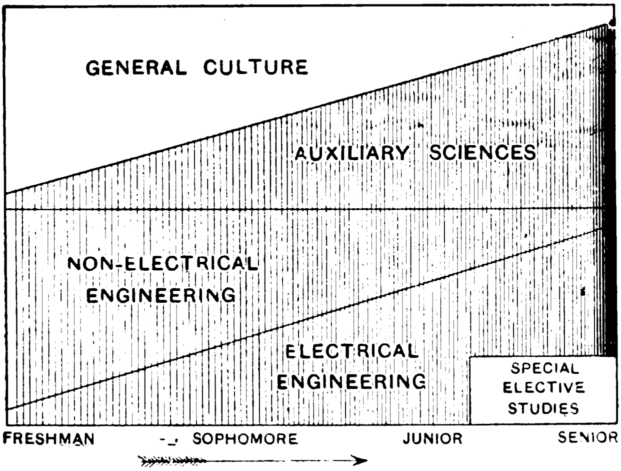
Vladimir Karapetoff. In his paper "on the Concentric Method of Teaching Electrical Engineering" Professor Karapetoff outlines a four-year college course different from the usual courses in two respects:

1. The course begins with the practical descriptive side of engineering and gradually leads into the theory, contrary to the present system, which begins with the theory.

2. Each year is made as far as possible self-contained, so that the student's horizon is gradually "concentrically" widened, and he is prepared for lower practical positions after the very first year in the college.

Moreover, according to this method, the student does not need to select a particular branch of engineering the first, or even the second year. In the first year he gets a "cyclopedia" of electrical, mechanical, civil, and mining engineering, and is given a chance to judge for himself which branch he likes the best. In the second year he is again given an opportunity to select between the mechanical and the electrical engineering. In the third year he gets straight electrical engineering; and in the fourth year specializes in the mathematical and physical theory of his profession. He also chooses a few elective branches, such as electric railways, telephony, power transmission, design, etc.

The advantages claimed for the above arrangement of the courses are as follows:



1. The student selects his profession after having had an outline course in it, in parallel with a few other allied specialties.

2. The method of beginning with the practical side, in other words with the ultimate results, is more psychological than beginning with abstract auxiliary sciences.

3. The interest and the professional feelings in the student are early aroused.

4. He can spend his vacations more profitably, having had engineering courses from the start; he can also be interested in technical literature and societies earlier than is possible with the present method.

5. A possibility is created for producing "learned artizans" who have taken one or two of the early years, and may then be useful in practice as assistants, or can do independent work in newly opened parts of the country, etc.

6. The theory, being built on the known facts of experience, will be less abstract, and more in unity with the requirements of practice.

A paper to be presented at a special meeting of the American Institute of Electrical Engineers, New York, January 24, 1908.

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(Subject to final revision for the Transactions.)

ELECTRICAL ENGINEERING EDUCATION

BY CHARLES P. STEINMETZ

When in the following I dwell more on those features of our electrical engineering education which appear to me unsatisfactory, it is not that I overlook the many good points, but rather that a criticism of the few defects appears to me more important, for the purpose of urging their elimination.

In general, the conditions for a good electrical engineering education in the United States are far more favorable than anywhere else; for an electrical engineering industry developed to a higher degree and to a greater magnitude than in any other country offers a very large field of application to the graduate engineer, thus supplying an incentive to enter this profession. Unlike other countries, where some opposition to the college-trained man, as unpractical, still lingers, the electrical industries here prefer, and in many instances demand, a technical college training for their engineering staffs. There is a tendency now to demand this training even for administrative and commercial positions. This leads to a close coöperation between the electrical industry and the engineering college. The leaders of the industry take a close and active interest in technical educational work, while teachers of engineering consider it as their foremost duty closely to follow and keep informed of the advances of the electrical industries, sometimes even are actively engaged in industrial work; and as early as possible the students are introduced to the industry, by visits to factories, inspection trips etc., which become more and more an important part of the college education. This is as it should be, and probably constitutes the strongest features of American engineering education.

While many, especially smaller colleges, are not financially strong, in general the means available to the American college of engineering are far superior to those abroad, and especially in erecting engineering buildings, laboratories etc., much has been done.

The great defect of the engineering college is the insufficient remuneration of the teaching staff: the salaries paid are far below those which the same class of men command in industrial work, and as result the college cannot compete with the industry for its men, but most of the very best men are out of reach for the colleges. The teaching forces of the colleges therefore consist of: 1. A few of the very best men, who are specially interested in educational work to such an extent that they are willing to sacrifice financial returns for it. These men have made the engineering college what it is; but even many of these men are ultimately forced by considerations of family etc., to leave college work and enter industrial employment. 2. Many younger men interested in teaching, enter college work to give it a trial. Some of these remain, but many return to industrial work, when they are forced to realize the small prospect of financial return offered by the college. 3. First-class men who devote a part of their time to the college and a part to industrial work, usually consulting engineering. This arrangement is probably the best for the college, handicapped as it is by the policy of salaries which may have appeared sufficient in branches in which no industry competes, but which are suicidal in the engineering department. Still it would be far preferable if the colleges could get the benefit of the whole time and the undivided interest of these men.

It appears to me, therefore, that a vast improvement could be made in electrical engineering education if a large part of the sums which now are devoted to marble engineering buildings and fancy laboratory equipments could be devoted to offer such salaries as to make available to the colleges the undivided time and interest of the best men in the field. The name of the donor may just as well be perpetuated by the professorship which he endows, as by the pile of marble which he erects for the college. After all, engineering buildings and college laboratories are of very secondary importance compared with the qualifications of the teacher and his assistants.

To the subjects taught and the methods of teaching very grave objections may be made. The glaring fault of the college curriculum is that quantity and not quality seems to be the object sought: the amount of instruction crowded into a four years' course is far beyond that which even the better kind of student can possibly digest. Memorizing details largely takes the place of understanding principles, with the result that a year after graduation much of the matter which had been taught has passed out of the memory of the student, and even examinations given to the senior class on subjects taught during the freshman and sophomore years, reveal conditions which are startling and rather condemnatory to the present methods of teaching.

It stands to reason that with the limited time at his disposal, it is inadvisable for a student to waste time on anything which he forgets in a year or two; only that which it is necessary to know should be taught, and then it should be taught so that at least the better student understands it so thoroughly as never to forget it. That is to say, far better results would be obtained if half or more of the mass of details which the college now attempts to teach, were dropped; if there were taught only the most important subjects—the fundamental principles and their applications—in short, all that is vitally necessary to an intelligent understanding of engineering, but this taught thoroughly, so as not to be forgotten. This, however, requires a far higher grade of teachers than are needed if the mere memorizing of text-book matters, reciting them, at the end of the term passing an examination on the subject and then dropping it. The salaries offered by the colleges are not such as to attract such men. When the student enters college he is not receptive to an intelligent understanding, for after a four years' dose in the high school of the same vicious method of memorizing a large mass of half and even less understood matters, the student finds it far easier to memorize the contents of his text-books than to use his intelligence to understand the subject-matter. After graduation, years of practice do for the better class of students what the college should have done—teach them to understand things. It is, however, significant that even now young graduates of foreign universities, in spite of the inferior facilities afforded abroad, do some of the most important electrical development work of this country. Men who never had a college education rise ahead of college graduates. This would be impossible if our college training gave what it should, an intelligent understanding of electrical engineering subjects.

The cause of the fault is perhaps the same that leads to the erection of engineering buildings and laboratories while underpaying the teaching staff: the competition among the colleges. To the father who looks up a college for his boy, marble engineering buildings and fancy laboratories are impressive, and so is an extensive curriculum; the result is a rapid increase in the number of students; but it is not to the benefit of the student, since the faster a subject is learned the faster also it is forgotten, and to become and remain thoroughly familiar with a subject, it is necessary to keep up the study of it for some years. While it is a good feature to insure application of the student by term examinations etc., this becomes harmful if it leads to dropping the subject at the end of the term. The least that can be expected from the college is that at the time of graduation the student still knows all that he has been taught during his college years. To accomplish this it is necessary to keep up the study of every subject to the end of the college course. This is not the case at present.

The different colleges vary between the school teaching the trade of electrician, and that attempting to give an intelligent electrical engineering education. At the one extreme is the college which dropped from its curriculum everything not required in electrical engineering. Such a school covers a large ground in electrical engineering, may even consider shortening the course to three years. The graduate of such a course is a full-fledged electrical engineer, capable to ply his trade, just as a plumber or brick layer when graduating from his apprentice years, and just as helpless and useless when any occasion arises requiring general knowledge to enable him to understand matters beyond his trade. The unavoidable result of such training is, that when with the development of the industry subjects become of importance which were not considered as pertaining to the trade of electrical engineering during his college years, his usefulness is impaired, younger men rise above him, and he cannot hope to rise beyond a subordinate position. Fortunately, the better technical colleges realize that the first requirement of an electrical engineer is a thorough general education, and begin to realize that for this purpose it is not sufficient to require general subjects for college entrance and relegate their study to the high school: for even if the average high school were what it should be and not what it actually is, much of the general knowledge required by an educated man cannot be taught in the high school, since during the high-school years the intelligence of the boy is not sufficiently ripened for its grasp, and a review in the college is necessary.

However, even if an attempt is made to teach or to review general subjects, the work is not carried sufficiently far. Mechanical engineering, physics, chemistry, and some civil engineering subjects are recognized as legitimate subjects of teaching in the electrical engineering course in many colleges, together with literature, some history etc.; but physiography, physical geography, meteorology, mineralogy, astronomy etc., are also of importance in a general engineering education. The failure to recognize this may sometime be a severe handicap to the electrical engineer, and that in the not very far future, judging from the present trend of development. In this direction the student, as well as his parents, are frequently antagonistic, and cannot see why subjects should be studied, which to their limited horizon appear unnecessary.

The instruction given in those branches of science, a knowledge of which is required by the electrical engineer, but to which only a limited time can be devoted, as chemistry, civil engineering etc., frequently is very unsatisfactory, being unsuited to the requirements of the electrical engineer, and, as result, of very little if any value to him. A general knowledge of these branches is required, so as to familiarize the electrical engineer with the general problems, methods, and purposes of the science; to enable him to understand subjects dealing with these sciences. The ability actively to practise the science is not required. To illustrate in the case of chemistry: the electrical engineer should have a knowledge of the laws of chemistry, a familiarity with the elements and their compounds, and a general knowledge of the methods of analysis and synthesis. Such a course must, therefore, necessarily be largely descriptive, and the experimental work largely illustrative. The same course is frequently given to the electrical engineer as to the first few terms of the chemistry student: general inorganic chemistry of the most important elements, and qualitative analysis. While a first-class beginning of a course of chemistry, such a course leaves the engineer with a knowledge altogether too fragmentary to be of benefit to him, and the time spent in mastering the mechanism and the details of qualitative analysis is largely wasted, since the electrical engineer will probably never be called upon to make an analysis. If he attempted to do so he would probably fail. The beginning of a chemist's training is not suited to the chemical training of the electrical engineer, and the same applies to all other sciences to which a limited time is devoted in the electrical engineering curriculum. To give a general view and working knowledge to the electrical engineer of such an allied branch of science, theoretical discussions, especially mathematical, are usually very little needed and therefore undesirable. A characteristic case of spoiling a science to the student by mathematics is that of astronomy. Astronomy is one of the most interesting and fascinating of subjects. But where taught as a part of the general educational program, it frequently is all mathematics, and so hopelessly dry and repellent. It should be given descriptively, for in a short course on astronomy it is just as ridiculous to delve deeply into mathematics as it would be to start the teaching of geography with a course in spherical trigonometry. I believe that in the teaching of allied sciences our colleges and schools are still greatly inferior to those abroad; the result is very marked in the product of the colleges, in the inferiority of the general education possessed by our graduates.

It goes without saying that in all teaching the strongest endeavor should be made to correlate the different subjects, to show the students the close relations which exist between all the branches of science, no matter how different they appear at first sight; and to interest him by bringing home to him the practical importance of what otherwise would appear dry theory. For instance, by using in the teaching of mathematics, problems taken from engineering; to have him handle and operate machines before proceeding to their theoretical investigation; then to derive the constants of the theoretical investigation from experimental tests of the apparatus; and from these predetermine the performance of the apparatus under different normal and abnormal conditions and experimentally verify it.

In conclusion, the main defects in the present electrical engineering training in some of our colleges appear to me as follows:

1. The insufficient remuneration of the teachers, which makes most of the best men unavailable for educational purposes and is, therefore, largely responsible for the other defects.

2. The competition between colleges, which leads to a curri-

culum marked more by the quantity of the subjects taught than by the thoroughness of the teaching. The graduates are sent out with a mass of half understood and undigested subjects, quickly forgotten, and deficient in understanding of the fundamental principles and in the ability to think.

3. The tendency of some colleges to teach the trade of electrical engineering rather than educate intelligent and resourceful electrical engineers.

4. The unsatisfactory state of the teaching of allied sciences, which gives instead of general view and understanding of the science, a fragmentary knowledge of some details.

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GAS-ENGINE REGULATION FOR DIRECT-CONNECTED UNITS

BY CHARLES E. LUCKE

The speed of an engine may be expressed in revolutions per minute, or in terms of the linear velocity of the crank-pin in feet per minute. Revolutions per minute is rather more indefinite than crank-pin velocity in feet per minute, because feet per minute is accepted as not simply a measurement for a minute of time, whereas revolutions per minute more frequently is. Revolutions per minute may mean half the actual number of revolutions completed in two minutes or twice the number of revolutions completed in one-half minute, or it may mean the momentary rate of completing a revolution without any implied time. As there is a possibility of a lack of agreement on the implication in the term revolutions per minute, I should prefer to define the engine-speed in terms of crank-pin velocity in feet per minute, which can be expressed momentarily for any period of time, and does not imply any particular time. This velocity so expressed is the integral of the accelerating forces with respect to time, and in fact may be so defined according to the laws of mechanics.

The problem of regulation is really a problem of force balancing, and there are always two forces or two resultant forces in question: one a driving tangential force on the crank pin, the other a resisting tangential force at the same place. When these two forces are equal the acceleration is zero, and its integral, the engine-speed, is constant. If these forces are unequal there is a real acceleration, due to their difference, either positive or negative, and the engine-speed changes. The problem of regulation resolves itself into a demand for a balancing of forces at the crank pin after the desired speed is once attained. The exact solution of this problem is impossible and always will be, regardless of the type of engine or the conditions of operation. While it is impossible ever to keep the acceleration zero, and the actual engine-speed constant and of predetermined velocity, it is by no means impossible to keep the mean of these driving and resisting forces equal for certain periods of time, and the mean resultant speed any constant value desired. The prime variable in the problem is the resisting force, generally expressed in terms of load; but as load does not accurately describe actual resisting force, regulation cannot be directly studied from load alone and load must be resolved back to force. Practically all of the work that has been done in the solution of this problem of regulation in practice has concerned itself, either directly or indirectly, with the problem of securing a mean of equality or an equality of mean forces for some time-period, and a speed limitation by introducing heavy rotors.

This sort of study is decidedly useful but it does not give as clearly the nature of the problem or the available means of its solution as does the other point of view, which calls for a comparison of actual momentary forces and not mean forces, and further may lead to misinterpretation of results obtained. The problem of regulating steam engines has been discussed for many, many years; the problem of regulating gas engines for comparatively few years. By regulating I do not mean merely the preventing of undue and dangerous speeds, but the problem of securing uniform crank-pin velocities. There really existed no such problem calling for solution by mechanical engineers until electrical engineering developed a demand for a dynamo driven at a constant crank-pin velocity. The demand for this close regulation, therefore, is recent, but more recent still is the development of the large commercial gas engine. The methods and means for accomplishing regulation of steam engines have been very fully discussed, although the problem is by no means solved. There are many papers written on the subject, and a few of these will be examined. In general, however, they present limited data and only a part solution of the problem. An analysis of the problem of regulating steam engines will show it to consist of a few elemental problems, each equally important, some interdependent and some dependent. Some of these elementary problems are precisely the same for the steam engine as for the gas engine, and it is desirable that those interested in solving the gas-engine problem should have a clear understanding of what has been accomplished in the regulation of the steam engine. It will be found that a good many of the steam-engine problems have been fairly well solved, and this experience can be applied directly to the gas engine; but there are certain characteristics of the gas engine which must be separately treated and which differentiate its regulation problem from that of the steam engine.

Among the numerous papers on regulation and engine governing, all the early ones are concerned with governors. Until about 1898, when parallel operation of alternators became an important problem, it is surprising what a large amount of the literature reveals the idea that engine regulation is a problem of governor design. While up to that time this may have been more or less justified in view of the kind of regulation necessary, it is no longer the case; governor design, important as it is in limiting mean speeds and keeping mean speeds at high and low loads close together, is to-day only one factor in solving problems of regulation calling for uniform crank-pin velocities. Following two or three years' strenuous experience in regulation of steam engines for driving alternators in parallel, there appeared a remarkable series of papers before the American Society of Mechanical Engineers and the American Institute of Electrical Engineers setting forth the problem and giving some of the experience gained.

It is rather a noteworthy fact and coincidence that during the same period the gas engine as a competitor of the steam engine for general power purposes came into rapid development. At first economy was sought, and found; then life and low maintenance, which to-day is still a problem, together with gas-engine regulation for electrical work and the design for special service of special gas engines.

An examination of the early papers on governors will show that the design of masses developing centrifugal and so-called inertia forces for controlling valve-gears is fairly well understood. Barring the unknown elements of windage, friction, and valve-gear resistance, the problem is one of simple mechanics. The papers on steam-engine regulation show considerably more concerning the problem. Some of the important ones are worth a review, but first a few elementary principles will clarify the situation.

Every engine has some form of valve-gear. This valve-gear is intended to distribute steam in steam engines; to measure air and gas in gas engines, mix them, distribute the mixture, ignite it, and then more or less expel the products. This valve-gear, in engines intended for speed regulation, is adjustable either wholly or in part. The adjustable part is adjusted to enable the engine to do an amount of work commensurate with the resistance or load. A certain number of strokes is necessary for a complete cycle of operations. When the work done by the engine in this complete cycle equals the resisting work or the load, the engine will always have at the end of each cycle the same speed as at the beginning, however it may vary during the execution of the cycle.

A change in the position of the valve-gear will change the amount of work the engine is capable of doing by a change either in the steam distribution or in the handling of explosive mixtures. If the engine is to be commercial, the first requisite is that the amount of work the engine is capable of doing must be dependent upon and determined by the position of the adjustable part of the valve-gear, and that for any given position of the valve-gear, regardless of all previous positions, the engine should be capable of doing the same amount of work every time the gear reaches this position. The amount of work done by the engine is proportional to the area of its indicator card, so that the first requisite for an engine capable of close regulation is that for any given position of the valve-gear there must always be produced the same area of indicator card, and for any other position a different indicator card, different in area, and possibly, although not essentially, different in form. To fix the position of the adjustable valve-gear there is but one principle employed, and that is to leave it to the control of the centrifugal force acting through the governor. The centrifugal governor contains elements which have fixed positions for every speed. These elements are connected with the valve-gear so that it will have a fixed position for every different speed. With this combination, therefore, of a governor and valve-gear having a fixed position for every speed and an engine-control valve, igniters, etc., giving a fixed amount of work and a fixed indicator card for every position, there will result a mechanism in which the amount of work done per cycle by the engine will depend upon the speed. It is always the same at any given speed and cannot be changed without first changing the speed.

Different designs of governors containing different distributions of the masses, different fixed speeds, and arrangements of parts differ only in their ability to move the valve-gear a certain distance against a certain resistance in a certain time with a given speed-change. It is a problem of simple mechanics with a few unknown elements to design a governor that will, with any given change in speed, 1%, 2% or x% above or below the mean or average for the cycle, move any valve gear, however strongly it may resist, through any distance it may be necessary to move it, and as quickly as may be necessary. It may be assumed as entirely feasible, and not by any means difficult, to design a governor that will accomplish any valve adjustment in as short a time and with as small a speed as may be desired. There must be, however, a speed-change before the governor gear can move, and if the engine is capable of doing a constant amount of work per cycle for every governor position the amount of work per cycle it can do will depend upon the governor positions or speed. The mean speed for the cycle will be constant when the work of the cycle done is equal to the resistance work; therefore. for an absolutely steady load, in which the resistance per cycle is equal to the effort of the cycle, the mean speed will be constant and the governor stand still holding the valve-gear still.

To be strictly correct, the above statement should be modified because centrifugal governor position does not depend upon the mean speed for the cycle but upon the actual momentary speed, together with the inertia, friction, etc., of its parts and attached gear. If the work done per cycle is exactly equal to the resistance work for the cycle, then the mean speed will be constant, but the actual speed during the cycle may vary very much. Consequently, the valve-gear may change position during the cycle, which may or may not have, but probably will have, some effect upon the work to be done. To stand perfectly still all the time, the governor must be subject to a constant speed. This can be obtained only with a persistent equality between the driving force and the resisting force, irrespective of the work per cycle. Should the forces change throughout the cycle, the governor position will change, cylinder distribution change, and there would be a continual changing of work done, alternately increasing and decreasing. This is all due to the fact that the crank-pin forces throughout the cycle do not maintain equality and the valve-gear and work done per cycle depend, not on mean speed, but on actual speed in every instance, which is a consequence of the equality or inequality of the two crank-pin forces. With a centrifugal governor, therefore, even if the engine were capable of giving the same area of cards for every governor position, there cannot be a constancy of speed with a variation of resultant crank-pin force throughout the cycle. The governor may be damped; that is to say, it may be made less sensitive to speed changes either by dash-pots or other devices, in which case it becomes, not a simple centrifugal governor, whose position depends upon actual momentary speed, but a modified centrifugal governor whose position depends upon a sustained speed or mean sustained for some definite length of time. For such a governor to be perfect in its modifications it should have a position consequent on the mean speed for the cycle and not upon the actual momentary speed at any instant. If it had a position depending upon the mean speed for the cycle, then the valve-gear would stand still when the work done was equal to the load for the cycle, regardless also how the actual speed may have changed. The actual speed in such a case will change throughout the cycle, but the mean will be constant for the entire cycle and a predetermined speed reached at the end of every cycle with no undue hunting of the valve-gear from an over-sensitive governor in combination with a widely varying difference between widely varying crank-pin forces. If there were an actual equality between the driving force throughout the cycle such damping of the governor would be harmful instead of beneficial.

Since the valve-gear position in any case depends upon the governor position, and this upon the speed, it is certain that the valve-gear will not have the same position for high and low speeds or at the same time when little work is being done the speed cannot be the same as when much work is being done, the amount of work in each case being dependent upon the position of the valve-gear. In an engine producing the same indicator card for any position of the governor gear, which is controlled by a centrifugal governor, the no-load speed must be higher than the full-load speed, though each mean cycle speed may be constant if the load is constant.

If the actual load varies from time to time throughout the cycle of the engine, giving the mean load a constant value for the cycle, the effect will be the same as that obtained with a constant actual resistance and a more widely varying actual effort, so that to prevent an untimely change in the valve-gear position due to a momentarily changing governor position, as a result of this crank-pin force discrepancy, the centrifugal governor will have to be a modified centrifugal governor of the type that aims to maintain a fixed governor position for the mean speed of the cycle rather than for the actual speed. The modification of a governor to secure this aim, as was mentioned above, of the dash-pot order, involving some resistance to its motion, or it may be a long belt that will take up any flapping and stretching momentary changes, driving a governor having considerable inertia—in any case the actual speed-change due to discrepancy between the forces driving and resisting may be reduced by fly-wheel inertia. This is really all that a fly-wheel does in an engine. It plays no part whatever in the adjustment of the equality between the work and the load, but reduces the actual speed changes due to disturbing differences between the driving and resisting forces. No matter how big the fly-wheel, these speed-changes will exist and last for just the same periods of time as the difference between the driving and resisting forces. Pure inertia governors have not a steady position dependent upon the speed; they are dependent on the rate of speed-change for their motion, and are useful only in connection with centrifugal governors, to bring about a quick change in valve-gear.

It has been said that the design of these governors to accomplish the desired motion of the valve-gear any instant of time, regardless of resistance, is a simple method. It is, if all the elements are known. Books on mechanics enable us to equate resisting and driving moments in which the forces and loads, centrifugal forces, valve-gear inertia, pin and bearing friction, and possibly steam or gas friction, and windage. It is possible to find all of the existing windage. In some recent tests in the laboratories at Columbia University, I have been able to show that the motion of the governor is in some cases not more than one-half that found by neglecting friction and windage in the governor itself. The other elements unknown are valve-gear inertia and mechanical friction, but it should be possible to evaluate these by simple test, although very little data on the subject are in existence. Even with all these elements known, it may be extremely likely that cases will rise calling for very large governors due to a desire for prompt action against considerable resistance on the part of the valve-gear, having a considerable motion between full-load and no-load positions. To avoid making these very large governors, the indirect system of governing has been developed in which the governor controls no more than a pilot valve, which in turn distributes fluid pressure to pistons controlling the gear proper. These pistons, with their pilot valves under governor control, involve another complication in arrangement, which, however, is for the sole purpose of avoiding too large sizes in the governor, but which plays no part in the regulation proper except moving the valve-gear as a simple governor might move it. In all these devices the position of the piston should coincide with the position of the governor, or, to put it otherwise, with rapidly varying actual forces and constancy of mean work, the piston-position should be constant and related to the mean speed for the cycle, while in this case the governor position may actually vary as it will.

With a constant load, the valve-gear attached to the governor may be at rest or in oscillatory motion, depending upon whether there is a difference between the actual forces, driving and resisting; whether the governor and valve gear move as a result of actual speed or a sustained or mean speed for the cycle. The discussion so far applies equally well to the steam engines and gas engines, and so far as the governor itself is concerned with its connection to the valve-gear, direct or indirect, simple centrifugal or modified centrifugal, with or without inertia elements there will continue to be no difference between the steam engine and the gas engine. So much of the regulation, therefore, that depends upon governor and fly-wheel design itself is absolutely the same for steam and gas engines, with possibly one exception, that of a simple governor taking on momentarily new positions, due to actual speed change as a result of momentary force-difference, which might appear that for the gas engine or the steam engine these force differences shown by the turning effort diagram may be more inconsistent for one than the other; as a matter of fact they are not except in special cases. It is after the valve-gear has moved under the influence of the governor, either from a sustained speed-change or momentary speed-change, direct or indirect, that the real difference between the steam engine and the gas engine is found. There is a slight difference that will be met with in the constancy of the indicator card for a fixed gear position. All the steam valve-gears, will give absolutely constant cards for fixed governor positions, while only the best gas engine can do this. The cycle of operations in a gas-engine cylinder or steam-engine cylinder occurs in a certain order and the control gear never affects all the phases of the cycle. If an adjustment is made after the susceptible phase has passed, no results will appear until all other phases have been completed. The indicator card of the steam engine can be affected positively during steam admission only, but there are cases in which the compression line will be correspondingly affected. If the governor should move during the admission period the admission may be immediately affected, and a change of effort immediately follow within the lapse of part of one stroke. With a single cylinder, single-acting steam engine, after cut-off, the governor can have no effect. Expansion must be completed, exhaust, and compression, so that if the governor moves the valve to the new position with cut-off, something over a stroke and approaching two strokes may elapse before a change in effort can occur. For this reason no single-cylinder, single-acting steam engine is employed for close regulation. By using a double-acting or two-cylinder engine one stroke can be cut out of this period which must elapse, or approximately one. By using more than one double-acting cylinder it becomes possible still further to reduce the cylic time, which must elapse between a change of valve-gear and new effort. The common type of large power-station engine is two cylinder, compound and often twin, giving four double-acting cylinders at some undetermined crank-angle, so that only a fraction of one stroke will have to elapse after a movement of the valve-gear before a change of effort, usually quite a small fraction.

The four-cycle gas engine may be regulated by the hit-and-miss governor, which is out of the question for close regulation since there is absolutely no attempt to graduate the effort. Next, there are throttling governors, which vary the amount of mixture by throttling the suction. There are others which admit a full charge during suction and expel part of it at compression by holding the valve open. Still another class, including oil-engines like the Diesel and Hornsby, admit fuel at or near the end of compression, and govern by varying either by the time of the injection or its length, generally the latter. Two-cycle gas engines of the Korting type may govern by acting on the suction of the gas pump with a throttle or delayed closure by any of the devices used on four-cycle engines, or it may govern by bleeding the charge in the gas chamber between the pump and motor cylinder. In both two- and four-cyle engines there may be an adjustment of the igniter. For reducing the time that will elapse between the valve movement and the beginning of a new effort the action should take place as late as possible in the cycle, which will give the effect as early as possible in point of time. For this reason a delayed opening on suction will be better than suction-throttling by a fraction of a stroke, and correspondingly the igniter action will be as prompt as affecting the admission as the steam engine. Equally prompt would be a fuel injection into compressed air at or near the end. No gas engine uses this. Unfortunately, however, for any igniter action, even a slight change will affect the economy and the range, is practically in only one direction. If the igniter is set right for economy, governor action can take place only to make it late and not to make it earlier with the proper effect. Making it late will reduce the effort and so will making it early, whereas an increase in effort is necessary in using this arrangement for regulating. In order to have a proper range for regulation by the ignition, the ignition should be normally set between properly early and very late, which gives poor economy. In any case where ignition is not used, as the beginning of a new effort, it may be assumed to take place on the beginning of combustion or the expansion stroke; the entire compression more or less must elapse between the valve gear at the charge and this beginning of combustion, a little less than a complete compression for delayed closure of the suction valve and a little more for the throttling action. In general it seems impossible to reduce the cycle of time to less than one stroke.

With this cyclic time it is useless to attempt to govern closely any engine with less than two double-acting, four-cycle cylinders, or one double-acting, two-cycle cylinder. It is useless to put a very sensitive governor or one of the highly refined inertia type on an engine that has been proved to be not worthy of it in the above mentioned respects.

A number of valuable papers on some of the phases of this regulation problem that are common to steam engines have appeared and a few of them will be examined.

Keilholtz: *A. I. E. E., October* 1901. In this paper a method for calculating the turning-force diagram is given, and the time, speed, and consequent angular variation from uniform rotary motion are calculated and experimental determinations reported. The paper is elaborate and involves a number of assumptions to simplify the work, but shows within the limits of experimental error and under conditions assumed it is possible to calculate true speed and to measure it so that the two results agree within the limits of experimental error. It is important to note, however, that the paper is confined to the case of constant resistance, equal to the mean effort, and the results depend for their value on the validity of these assumptions. Nothing whatever is determined concerning the effect of a fluctuating periodic load having the same constant mean, nor of the effects of load changes, nor the different speeds for different loads, nor the adjustment of effort and resistance by a true centrifugal governor, (whose position depends upon actual momentary speed), nor of a similar effect with the governor adjusted so that its position is determined for the mean speed for the cycle.

Slichter. Slichter notes a variation of speed: first, due to a change of load in which the average speed changes; secondly, irregularity throughout any given revolution or cycle while the mean speed is constant. He states that the adjustment of the mean is altogether a function of the governor and then drops the subject without pointing out the fact that no governor can accomplish this with a difference between driving and resisting efforts, if it is of the type whose position depends upon actual momentary speeds. The rest of Slichter's paper is taken up with the fly-wheel effects in reducing angular displacement from the mean or constant velocity positions with crank-pin force differences. The work is directed mainly towards alternators working in parallel, and the first problem for the solution is the determination of the crank-pin or pole displacements from true mean position, which will limit the cross-current to 10% of full load. In the course of his work he assumes the effort curve to be sinusoidal, which permits the development of a formula for a fly-wheel weight to limit the displacement. An example is worked out to illustrate the formula. Slichter however, aside from the errors introduced by taking the effort curve to be sinusoidal, makes the further assumption that the mean resistance is constant and equal to the mean effort. In other words, constant-load conditions only are discussed. He does however, make one important point, that when the alternators by any accident or fault of design get out of phase even slightly the actual resistance will be undulatory, although the mean may be constant.

Berg. Berg's paper is almost entirely electrical, and is concerned with the electrical conditions for parallel operation of alternators. The main feature with respect to regulation brought out in this paper is the pulsation of actual resistance with the constant mean when the alternators are slightly out of step, which is due to unequal momentary speeds of different machines in parallel, and which may be exaggerated by steam-effort impulses. It is not clearly pointed out that the real cause of exaggeration of these speed conditions is the fact that an alternator, taking positions due to momentary speeds, may be admitting steam in a pulsating way throughout a cycle, due to governor jumps when differences beween the actual effort wave and pulsating resistance becomes greater as the crests of the two waves may become opposed. The remedy observed is the use of a governor registering mean velocity for the cycle, and holding the valve-gear to the proper position for that mean. The means suggested by Berg is a dash-pot which is one of the ways of attempting to secure a mean velocity governor.

Steinmetz: *A. I. E. E., March* 1902. Steinmetz's paper is concerned with the problem of regulation with parallel alternator operation, and he notes three conditions to be examined: first a permanent change in speed due to a change in load. He points out here that there will be a different speed for every different load, the load, of course, being in any case a constant. This is an essential characteristic, as noted before, of centrifugal governors and their effects on the mechanism. Secondly, a temporary change in speed due to a change in load. In this connection he points out that on a change of load it is impossible for a governor to adjust the effort to the new resistance without the lapse of a considerable time. This causes a corresponding excess or deficiency of speed before the adjustment is accomplished. Thirdly, the periodic change of speed during "each revolution," which, of course, would be better read in "each cycle" as in some engines the cycle is not accomplished in one revolution. Steinmetz shows in this paper how important for the proper distribution of load between two alternators is this feature of having a different speed for every different constant load, and that a permanent drop in speed with increase in load is desirable. The absolute impossibility of a constant turning-effort diagram is shown, but the desirability and possibility of reducing variation of the turning-effort diagram by cylinder combination and crank-angles is pointed out, as well as the effect of reducing speed-changes for a given variation of effort by the fly-wheel. The periodic variation in speed, due to actual variation between effort and resistance, is assigned by Steinmetz as the cause of the hunting of alternators and synchronous apparatus, and he says that the effects are aggravated by the use of heavy fly-wheels. Steinmetz notes two kinds of hunting between alternators: forced surging, and cumulative or resonating surging. Forced surging is that due to momentary crank-pin-force differences, and cumulative surging is that due to certain electrical characteristics of the circuit, or may be assigned to the mechanical construction of the engine, especially the governor if the governor has a tendency to jump, which is explained as a tendency to take on a position due to momentary velocities.

Emmet. Emmet's paper is entirely concerned with parallel operation of alternators driven by steam engines and the effect of governor damping on the reduction of cross-current or surging. The paper gives examples of engines operating in Philadelphia and Boston. In Philadelphia it was found that the governor was in constant motion even with constant mean load, and that the indicator cards were consequently continually varying under the same constant load, as might be expected. The governor, when blocked, held the valve-gear in a constant position, and in this way absolutely constant cards were obtained. This shows that there was no fault in the governor and valve-gear as such, but rather that the load, although apparently constant in its mean value, was a pulsating one and the governor and valve-gear took momentary positions due to momentary speeds, due in turn to momentary force differences at the crank-pin. The fact that the surging was worse at times than at others is simply an indication of that fact noted above that while the mean load was constant and governor jumping could result with variation of effort, the pulsating load gave a wave of force, the crests of which sometimes coincide with and sometimes oppose the crests of the effort wave, giving, therefore, at times, a greater force-difference and at other times a less force-difference than with constant resistance. The trouble was cured by dash-pots on the governor, which had the effect of preventing the governor taking positions due to momentary velocities, and making it rather tend to assume a position due to mean velocity for the cycle. It was found in Boston that while similar surging existed and became less by the use of dash-pots, it could not be cured even when the dash-pot was strongly resisting the governor motion, as it permitted the mean speed to vary considerably. In this case, therefore, it appears that dash-pots may fail to accomplish the result of making the governor take a position due to the mean speed of the cycle, but, on the contrary, may actually resist any motion on the governor so that it becomes no longer a governor. This led to what has been called the "time-relay dash-pot," which is really no more than an improved form of modified centrifugal governor to make it more nearly fixed in position for the mean speed for the cycle without resisting an adjustment to a new mean. It is also interesting to note that Emmet reports a light fly-wheel better than a heavy one for successful parallel operation.

Rice discussing Emmet. Rice points out that a method of adjusting the fly-wheel weight by the allowable generator wheel displacements and the turning-force curve for the engine for constant load, but does not consider a variable load curve either periodically or irregularly variable.

Also on governors he states that they must have certain characteristics: they must be adjustable for speed-position to allow voltage adjustment and load distribution between machines; they must be adjustable with damping; they must have power enough to control speed in spite of damping; they must be switchboard controlled.

There is no discussion whatever in connection with this governor question by Mr. Rice of the period that must elapse between the governor movement and resultant effort change, nor of the limitations imposed by the cycle of operations on this period.

Seymour discussing Emmet. Seymour refers to the misapprehension of the specific nature of the requirements for parallel operation under which salesmen for engines and generators, as well as purchasers of the apparatus, may be laboring. He states that close regulation is generally interpreted to mean small differences between mean speed at no load and at full load, and points out that a small difference between these mean speeds is not a requirement of alternator parallel operation, and in fact it is better for load distribution between alternators that this difference be large comparatively. He next considers fly-wheel weights and says that a fly-wheel heavy enough for a uniform effort, when there is a discrepancy between driving and resisting forces, will increase the trouble from generator surging, referred to as "cumulative" by Steinmetz. The importance of noting the period of governor jumps, and the period of the varying resisting forces coinciding with the variable effort-crests, when the alternators are slightly displaced, is given some attention. The impossibility of correcting faults by governors alone is also pointed out when undulatory resisting-crests oppose undulatory effort-crests. Seymour does not state it quite this way, but this is in effect what I understand he means. He then gives some experimental data on the regulation of engines built by his firm.

Scott discussing Emmet. Scott first draws a parallel between parallel operation and two engines driving generators by gear wheels on the same shaft. Scott also notes the importance of the periodicity of governor jumps synchronizing with the periodicity of the maximum difference between driving and resisting forces, shown by the effort and resisting force; but as in the case with Seymour he does not state the situation quite this way. The point he makes is the special importance of noting the periodic nature of the electrical load in certain cases even when the output is constant, and gives examples of an alternator, which worked satisfactorily on a lamp load but would not at all with a synchronous converter in the circuit.

Mershon discussing Emmet. By curves between speed and load, when load is constant, Mershon shows the importance of having a considerable difference between full load and no load for proper distribution of load between the machines, and shows by variation of these curves why the distribution may be more stable at one load than at another.

Steinmetz discussing Emmet. Steinmetz points out that a heavy fly-wheel is bad only because by reason of its great inertia it permits the governor to overrun resisting synchronizing after once displaced.

Behrend discussing Emmet. Behrend refers to two alternators abroad, driven from the same engine shaft, which would not run in parallel at all. This is a striking example of the periodic nature of an electrical load and shows the importance of realizing that electrical circuit characteristics are matters of as great importance in parallel operation as engine characteristics, and that a failure to operate satisfactorily in parallel cannot always be traced to the engine regulation.

Slichter: *A. S. M. E.*, 1902. Among other matters taken up similar to those in his other paper in the Institute he lays particular stress on the computation of displacement of the alternator by inconstant turning effort and shows that the cross-currents and magnetic pull on the rotating system depend upon the amount of displacement. The difficulty is greatest with the greatest number of poles. He refers to a paper by Longwell before the Engine Builders' Association on the "Synchronization Torque of Generators" due to the displacement from the mean position where the torque is proportional to the displacement. The displacement is greatest also at the time when the disturbing effort is greatest, so that the two effects of synchronous torque and displacing effort torque are additive, and being additive are cumulative, helping to put the generators out of step. Some examples are given involving turning effort curves and computations of displacement.

Longwell discussing Slichter. Longwell first refers to a paper by Rosenberg, engineer for Korting Bros., gas engine manufacturers in Germany, in the *Electro Zeitschrift*, 1902, in which the cumulative effect of the magnetic pull and the disturbing irregular turning forces are shown to be impossible of prediction, and dependent upon the type of engine among other things. Mr. Longwell concludes that no mathematical treatment of this subject is adequate. This is true because the effect is partly mechanical and partly electrical and not all of the variables, either electrical or mechanical, are known.

Astrom, A. S. M. E., 1901. "Fly Wheels and Angular Variations." First there is given a complete calculation of turning effort and the effects on turning effort of the mechanical forces, due to reciprocation parts, rotary parts, gravity elements, and the connecting rods which partly rotate and partly reciprocate. This concludes with a number of turning-efforts diagrams and variable-load curves for pumps and compressors, enabling the crank-pin force difference curves to be plotted. The coefficient of fluctuation of speed for different classes of machinery are given in fractions of the mean, but it is pointed out that as machines of the same class with the same coefficient of speed fluctuation do not work equally well, it is evident that a small coefficient does not assure satisfactory speed regulation. The consequent displacement from the mean position is then developed as a substitute for the coefficient mentioned in fixing a unit regulation, and is shown to be the result of double integration of the force curve. Some turning-effort curves are given for steam engines at full load and light load, and the effects of different crank-angles on the uniformity of effort together with the reduction in fly-wheel weight for equal regularity of motion computed. Astrom makes only one reference to load changes and makes no attempt whatever to get results in speed changes.

Abbot discussing Astrom. Abbot gives a complete calculation for a steam engine, in which the coefficient is as small as one-three-thousandth and the displacement 2.5 electrical degrees when calculated by the usual method of turning-effort diagram with mean effort equal to mean resistance and resistance constant. No reference whatever is made to variations in resistance.

Paper by Dr. Franke, on the coefficient of irregularity. L' Eclarage Electric. In this paper there is a discussion concerning the coefficient of irregularity or speed steadiness for alternating-current and direct-current machines, and it is stated that this unit is a very satisfactory one for judging a direct current machine, as it represents very nearly the variation in voltage and the flickering of the lamps. ·1/200 is considered to be good, and as low as 1/80 satisfactory, while 1/65 is considered impossibly bad. It is pointed out that with a single-cylinder, four-cycle gas engine 1/80 and 1/100 should easily be obtained without abnormal fly-wheels and these machines can, therefore, be depended upon for satisfactory voltage regulation. No reference, whatever, is made to what will happen on the change of load; this is based on the usual method of calculation for constant load and mean effort. With respect to alternators: it is pointed out that if the coefficient is too small the result will probably be worse than if it is not small enough. He considers 1/200 quite satisfactory. It is pointed out that cross-currents tend to accelerate the lagging machine and retard the leading, and the accelerating force or magnetic pull depends not at all upon actual speed but on the displacement of the poles, and that heavy fly-wheels resist in bringing into its proper place a pole once displaced, although it would seem at first to be sufficient guarantee against displacement initially. Light fly-wheels are recommended as better than heavy ones, but there is no means given for judging their weights except the old rule of computation of constant resistance with variable turning effort.

Summarizing the variations of conditions entering into the regulation problem under the headings of load, effort, governor, fly-wheel, and valve-gears, we have the following:

Kind of load.

1. Load may be constant and equal to the mean effort.

2. It may be constant and greater than or less than the mean effort.

3. Load may be undulatory, having a mean equal to the mean effort.

4. Load may be undulatory with a mean equal to the mean of an undulating effort.

5. Load may be constant at a maximum.

6. Load may be constant at zero.

7. Load may suddenly change from one constant value to another constant value, up or down.

8. Load may suddenly change from an undulatory with a constant mean to another undulatory with a constant mean.

9. Load may suddenly change from an undulatory with a constant mean to a constant.

10. Load may change from any value to an undulatory with a constant mean.

11. Load may change from an undulatory with a constant mean to another undulatory with a constant mean.

12. Load may change from any irregular value to any other irregular value with no particular relation between.

13. The time at which the load changes may occur at the most favorable point of the cycle for a change of effort.

14. The time at which the load changes may occur at the most unfavorable point of the cycle for a change of effort.

15. The time at which the load changes may occur at the same point between most favorable and unfavorable point of the cycle.

Kind of effort.

1. The effort may be absolutely constant for full load and a maximum.

2. Effort may be absolutely constant at zero.

3. Effort may be constant at any value between maximum and zero.

4. Effort may be regularly undulatory with a constant mean for each cycle.

5. Effort may be irregularly undulatory with a constant mean for each cycle.

6. Effort may be irregular with a constant mean for two cycles.

7. Effort may be irregular with a constant mean for no full number of cycles.

8. Effort may be that for a steam engine, single cylinder, with low or high inertia.

9. Effort may be that for a double-acting, single-cylinder steam engine with a low or high inertia.

10. Effort may be that for any number of cylinders of the double acting, simple, triple, compound, etc., with a low or

high inertia of any number of cranks spaced in any particular way.

11. Effort may be that for a single-cylinder, four-cycle gas engine, single acting, low or high inertia.

12. Effort may be that for a single-cylinder, single-acting, two-cycle engine, low or high inertia.

13. Effort may be that for a single-cylinder, double-acting, four-cycle gas engine, low or high inertia.

14. Effort may be that for a single-cylinder, double-acting, two-cycle gas engine, low or high inertia.

15. Effort may be that for a two- or four-cycle engine, single or double acting, with any number of cylinders, low or high inertia, with any number of cranks grouped at any particular angle.

16. The fly-wheel may be light or heavy with large or small mean diameter.

Governors:

1. The governor may be a simple centrifugal governor, taking a position corresponding to the momentary actual speed.

2. The governor may be a modified centrifugal governor, taking a position not due to the momentary actual speed.

3. Governor may be of a modified, centrifugal type, taking a position due to the mean speed for the cycle.

4. The governor may or may not have inertia elements to affect the promptness of the motion of the valve-gear independent of actual speed, but depending on momentary acceleration, positive or negative.

5. The governor may be large or small with ability to move the valve-gear through large or small distance in short or long periods of time, against large or small valve resistances.

6. All the simple, centrifugal types or modified centrifugal types with or without inertia effects.

Valve-gears.

1. Valve-gears may affect the cycle so as to change the effort immediately.

2. Valve-gears may be so designed as to affect the cycle only with the lapse of some part of the cycle or some part of more than one cycle.

3. Valve-gears may be heavy or light with or without gravity resistance in one direction, with or without gravity assistance in the other direction, with or without inertia resisting its motion with high or low frictional resistance through change of position.

To study adequately all the conditions appearing in this summary, including the unusually large number of variables under the five groups, more or less dependent, is a very tedious matter, but nevertheless worth while. I think, however, from the review of the papers given, it seems pretty clear what is the function and limitations of governors or fly-wheels. From the large number of turning-effort diagrams, steam and gas engines, the nature of this effort-curve and its change with load, cylinder combinations, grouping of crank-angles, different inertias and reciprocating parts, have become fairly well known. To those not familiar with such turning-effort diagrams of gas engines, reference may be had to Guldner, Haeder, Lucke, and numerous papers. A comparison of the gas engine, turning-effort diagram with that of the steam engine will show that it is possible to secure as regular an effort curve for the gas engine as for the steam engine; regular with respect to the number of fluctuations above or below the mean, and with respect to the value of the coefficient of fluctuation. That is to say, that the turning-effort diagrams for the gas and steam engine are equally good as computed under the constant load condition, and this is the only basis on which they have been computed. What happens when the load changes and before the governor has had time to balance the effort with resistance, will be different for the two classes of engine and different again for individual examples of each class.

The things that have not received much attention, or anywhere near adequate attention are:

A. The electrical effects in producing variables actual resistance at the crank-pin for constant bus-bar loads.

B. Cyclic interference between governor control and effort effect.

C. The speed-change due to load-change due to a period of unbalance exaggerated by cyclic interference and pulsating effects, which cannot be overcome by any refinement of governor construction and which are just as likely to require light as much as heavy fly-wheels on the engine, but which probably can be met in the gas engine by a change in valve-gear control functions or a change in cycle.

Just what can be accomplished along these lines can only be determined by plotting force diagrams representing driving and resisting forces for each moment of the cycle, and in connection with each force-diagram a consequent velocity-diagram obtained by the integration of the force or accelerating diagrams. The force used in this integration will be the algebraic sum of the driving and resisting forces of each moment, and if both are varying they may be additive or subtractive.

To illustrate this method of treatment the following sketches are presented, not as a solution but solely to illustrate the method of procedure. Fig. 1 shows the force-diagram and velocity-diagram for a steam turbine with a constant-resistance load. This diagram shows a full-load and light-load force and speed curve and indicates that the light-load speed is higher than the full-load speed and instead of being exactly constant are nearly so with constant mean. The effort curve on the turbine slightly rises and falls fairly regularly for a constant resistance, which is shown by the dotted line.

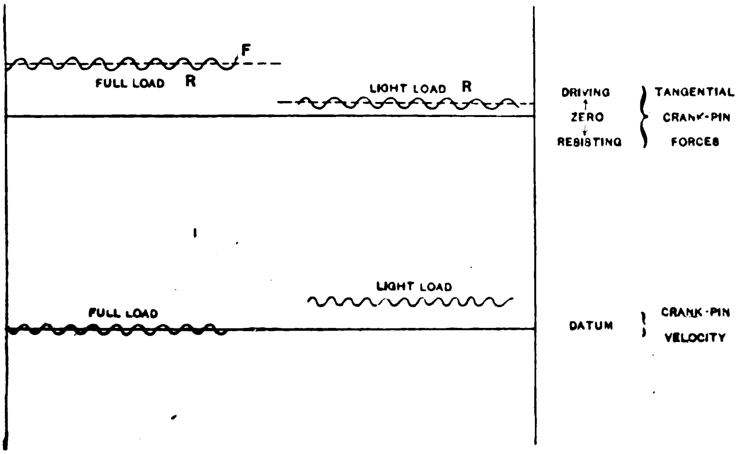

Fig. 1—Steam turbine resistance constant, effort pulsating constant mean

Fig. 2 shows a variable resistance of a wave-form nature and a similar waving effort, both with constant mean. The velocity-diagram for these conditions will involve greater waves than before or greater fluctuations above and below the mean, because the effort and resistance become additive at crests and hollows, even though the mean value of each is constant.

Fig. 3 shows force and velocity diagrams for a constant full load change to a constant light load with a corresponding jump in velocity during the period of governor action.

Such curves as these indicate clearly the fly-wheel effect, and show that it merely limits the maximum velocity during the period of unbalance and has no effect on the period of unbalance or the period of acceleration. These curves also show that the maximum velocity is attained after an acceleration when that acceleration has again decreased to the mean value. They will also show how the governor must override in its efforts to reduce a too high velocity to the required new mean value. If such curves are shown for steam and gas engine with their available effort-diagrams in place of these nearly constant turbine effort-diagrams, I think it will be easy to see how clearly the problem of regulation can be studied and also the effects of variable actual load at the crank-pin when they do or do not synchronize with the effort wave.

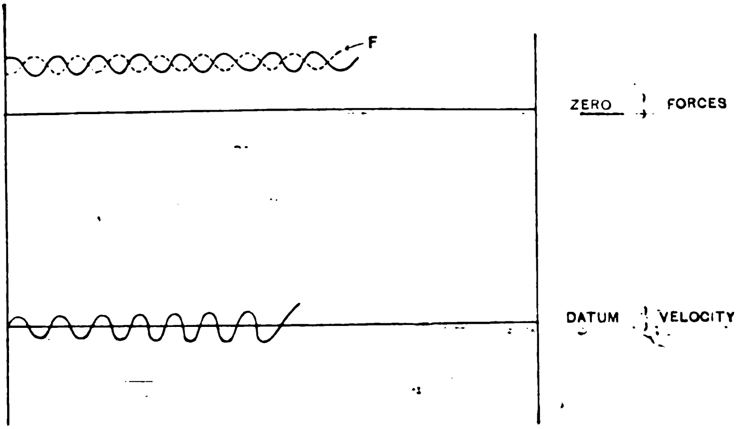

FIG. 2—Steam turbine resistance wave form constant mean, effort wave form constant mean, crests against hollows

There is no use in attempting to regulate a gas engine that will not meet the first requirement of absolutely invariable indicator card with the valve-gear blocked in position. This is the first difference between the problem of regulating the gas engine and the steam engine, and must be checked. Only the best gas engines will give such invariable cards. The next step is to run the governor with all valve-gear connected but with the engine at rest, the governor being driven from an external source to determine valve-gear positions at different speeds of the governor. This requires very accurate speed-measuring apparatus. The next experimental check is to measure the mean effective pressure obtainable at all different positions of the valve-gear, it being blocked during measurements and the engine held to about the proper speed with suitable resistance and the governor cut out. From this the speed horsepower curve should be plotted and there must be not too small a difference between mean speed at constant full load and the same at constant no load. The result should be checked by operating the engine with everything connected and a variable load. Every precaution should be taken to insure the governor operating valve from sticking either by tar or dust collection. The next important difference between the steam engine and gas engine regulation will come in as the result of cyclic interference in each. This requires calculation and experimental check to obtain proper data on the necessary sensitivness and type of governor fly-wheel effect, which should neither be too much nor too little in the light of the operation requirements.

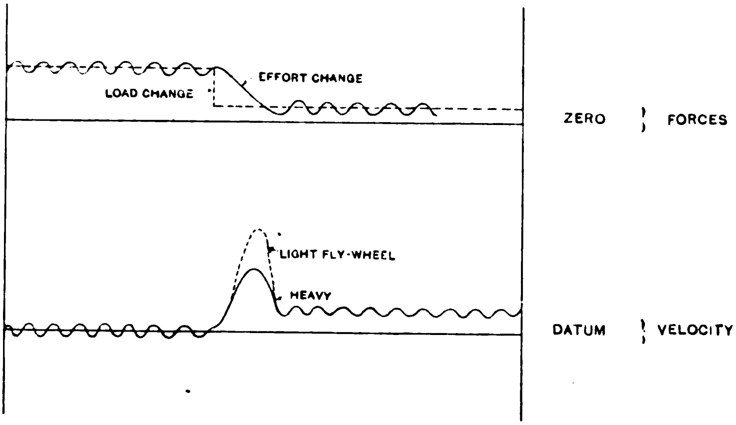

Fig. 3—Steam turbine load change, constant full to constant light

Failures to obtain proper regulation of gas engines from any of the causes mentioned, but chiefly from cyclic interference have been overcome or rather avoided by the introduction of flexible couplings, consisting of leather link, spring, friction slip joints, centrifugal devices, all of which are intended to allow the driven rotor to move at a uniform speed, even though that of the driving engine should fluctuate. These devices have never been used on large units and are by no means solutions.

Large gas engines are operated fairly satisfactory with twenty-five cycle alternators and the cyclic interference, while it is always noticable is not prohibitively bad. With 60-cycle work this is not the case, and gas-engine-driven, 60-cycle alternators must be so far pronounced unsatisfactory, though some are doing well. Considering the nature of the problem; its newness, its difficulty, and the more insistent demands of the public for economy of fuel, and ruggedness of construction than for close regulation up to the present time, I think that the gas engine has done extremely well. The wonder is, then, not that the gas engine cannot regulate as well as the steam engine, but that it regulates as well as it does. In the light of all this I feel that the gas engine has only just started on its career of usefulness.

In conclusion I believe that an intelligent examination of the nature of the problem of gas-engine regulation and the study of numerous diagrams, force and velocity, of the kind here presented, will result in the elimination of many of the present handicaps of the gas-engine cycle and make possible regulation as good as that of the steam engine.

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THE NON-SYNCHRONOUS GENERATOR IN CENTRAL STATION AND OTHER WORK

BY W. L. WATERS

That an induction motor could act as a generator and return power to the line when driven at a speed above that of synchronism, has been known for many years. It has, however, always been regarded as more or less of a scientific curiosity, and except in the case of the Swiss three-phase mountain roads, where the motors are sometimes allowed to run as generators to brake the train on descending heavy grades, the non-synchronous generator has had but few commercial applications. The fact that the characteristics of this generator are such that it must receive a lagging current from the system, the magnitude of which is for a given machine definitely decided by the slip of the generator above synchronism, combined with the fact that when connected to a circuit is has no definite voltage and frequency of its own, make it lack the flexibility of the synchronous generator. In 1895, Mr. B. G. Lamme proposed running a non-synchronous generator with an unloaded synchronous motor, the generator to supply the watt component and the motor the wattless component of the current in the system. But though this suggestion rendered the non-synchronous generator a practical machine, it is easily understood that on account of the lesser flexibilities when compared with the synchronous generator, it has not appealed to the central station engineer as a desirable addition to his equipment.

The question as to the advisability of adopting the non-synchronous generator for power station work, was decided adversely by engineers at the time when steam engines and water turbines were the only practical prime-movers. But to-day we have to deal with steam turbines and gas engines, and the coming of these two new types of prime-movers has altogether changed the situation in regard to the use of this generator for power station work. It often happens in such cases that the real meaning and possibilities of the introduction of types of machinery with such fundamentally new characteristics as the steam turbine and gas engine, are not recognized until they are accidentally forced upon us. This has been the case in the present instance; the question of the use of non-synchronous generator with steam turbines was not seriously considered until it was brought up indirectly. In 1904 a copper smelting and rolling company was installing a 1200-kw., 200-volt, direct-current generator for electrolytic work. It was desirable to continue the good steam economy on variable loads, the small floor space and reduced maintenance of the steam turbine, and at the same time to generate 200-volt direct current. A 1200-kw., 6000-ampere, 200-volt, 1800-rev. per. min., direct-current generator was not considered practical, and a non-synchronous generator together with a synchronous converter was suggested as an alternative. It was finally decided to adopt this type of equipment, and a 1200-kw., six-phase, 140-volt, 30-cycle, 1800-rev. per min. generator together with a 1200-kw., six-phase, 150-rev. per min. converter was installed to supply the required 6000 amperes direct current at 200 volts. A direct-current exciter for the converter was provided, so that the voltage of the converter's direct-current could be varied from 100 to 230 volts without any danger of instability. The exciter is compound-wound to give constant voltage on the direct-current side of the converter, and the power-factor gradually rises from about 25% at no load to about 96% at full load. When starting up the set, the converter is run up to speed from an auxiliary source of direct current, and the generator by its turbine. They are then thrown together, the generator driving the converter as a synchronous motor, and the converter supplying the magnetizing current of the generator. The governor of the turbine decides the frequency of the set, and the slip of the converter behind the generator is proportional to the load, being about 1% at full load. This equipment has been running now for about three years and operates perfectly. The generator is similar in arrangement to the old open-type turbo-generator, and in consequence is rather noisy, but with the modern enclosed type of generator it is possible to arrange the air circulation better, and to obtain as a result a much quieter running machine.

This installation is given in detail, as it is one instance where the adoption of this apparently inflexible type of generator resulted in an installation, which combines the flexibility of the standard direct- or alternating-current generator with the capacity for heavy overloads of the synchronous converter, and the reliability and robustness of construction of the non-synchronous generator. No other electrical equipment which could have been installed would have given the good results that were obtained. And though the existing conditions rather forced the choice of the equipment in this case, the results so thoroughly met expectations, that engineers began to consider whether the development of the last few years in regard to prime-movers had not changed the non-synchronous generator from a scientific curiosity, to a generator possessing great advantages for certain conditions of power station work.

General characteristics of the non-synchronous generator. As most engineers are more familiar with the characteristics and performances of the induction motor than they are with those of the commercial non-synchronous generator, it will be well to show how the characteristics of the two machines are allied. An induction motor of given characteristics carrying a certain definite load, runs at a fixed speed relatively to that of synchronism, and it takes a current the magnitude and phase of which are definite. The torque exerted by the motor is proportional to the product of the current induced in the short-circuited secondary, and the magnetic flux. The electromotive force and the current induced in the secondary, and hence the torque, are proportional to the rate at which the secondary conductors cut the primary magnetic field, that is, to the slip of the rotor above or below the speed of synchronism. As the speed of the motor gradually rises to that of synchronism, the current in the secondary, and the torque gradually fall, till at the speed of synchronism they both become zero. If the speed of the machine still continues to increase, the secondary conductors cut the primary flux in the reverse direction, and the induced electromotive force, the secondary current, and the torque become negative; that is, the machine requires a mechanical power to drive it above the speed of synchronism. The machine now returns electrical power to the circuit, and has become a generator. When running as a motor, the current is never in phase with the impressed voltage, for two reasons: (1), the motor requires a certain wattless magnetizing current; and (2), the motor windings, both primary and secondary have a certain amount of self-induction. This makes the current lag behind the impressed voltage by an angle ϕ, depending on the characteristics of the machine, and on the load it is carrying. When the machine runs above synchronism as a generator, it still takes from the circuit the wattless magnetizing current, and the circuits still possess their self-induction. And as the watt component has reversed in direction, this will mean that the primary current lags less than 180° behind the voltage impressed by the circuit on the generator, hence the current leads the electromotive force supplied by the generator to the circuit. Thus we have as a fundamental characteristic of the non-synchronous generator, that for a given load it runs at a certain definite speed above that of synchronism, and that, (*a*) it supplies a watt current which represents the power delivered by the generator to the circuit, and (*b*) it takes a wattless magnetizing current from the system, the magnitude of which depends on the voltage and on the watt component of the current. Hence this type of generator cannot supply a lagging current to the outside circuit, and can only deliver power to a circuit which can provide the lagging magnetizing current required by a non-synchronous generator: for any given speed, the magnitude and phase of the current which the generator will supply is definitely fixed. Also as the wattless component of the current varies in magnitude when the load of the machine changes, we must have in circuit some apparatus which can supply a variable amount of lagging current, and which will keep the voltage of the circuit constant. It is these apparently rigid and inflexible conditions which have prevented any extensive use of the non-synchronous generator, and it is only because under certain modern conditions these limitations do not mean serious disadvantages, that this generator is now put forward as an important part of a power station equipment.

Usually the load on a power station is either non-inductive or has a lagging power-factor, so that if this type of generator is used, the lagging current required by the generator, and perhaps also by the outside circuit, must be artificially supplied. There are two ways of obtaining the lagging current required by the non-synchronous generator: (1), from a condenser; (2), from a synchronous generator or an over-excited synchronous motor. It would not be desirable commercially, to install a condenser specially to supply the required lagging current, as the cost would be prohibitive; but a large cable system has quite a considerable electrostatic capacity, and the lagging current supplied by this system will usually help greatly in reducing the size of the necessary synchronous machine. In any case, however, it is necessary to have a synchronous machine, either a motor or a generator, in the circuit, in order to set the frequency and the voltage. If we have the non-synchronous generator running together with a synchronous generator, the latter machine supplies all the lagging wattless current required by the non-synchronous generator and the outside circuit, while the voltage of the circuit is decided by the excitation of the synchronous generator. The distribution of the watt component of the current between the two machines, is decided by the governors of the prime-movers. The load which the non-synchronous generator takes, depends on the percentage slip by which it leads the synchronous generator, and the remainder of the load is taken by the synchronous generator. When additional load comes on the station, it first comes on the synchronous generator, and then, as this machine slows down and allows the slip of the non-synchronous generator to increase, part of the load is transferred to this latter machine. In any case, the voltage regulation of the system is that of the synchronous generator, and the voltage of the circuit under any condition of load is decided by the excitation of this machine. If we have the non-synchronous generator running together with a synchronous motor or synchronous converter, then the same remarks apply. The voltage regulation is that of the synchronous machine, and the voltage of the circuit is decided by the magnitude of its excitation. When the load increases, the additional load comes first on the synchronous machine, energy being supplied to the system from the momentum of its rotating part. and then as the machine slows down a little, the load is transferred to the non-synchronous generator, the synchronous machine supplying simply the additional lagging current required by the generator when carrying the additional load. The synchronous machine supplies at all times all the lagging wattless current in the circuit, and the governor of the prime-mover driving the non-synchronous generator, decides the frequency of the circuit, the synchronous machine slipping behind the generator an amount just sufficient to allow this latter machine to supply all the power required by the circuit.

Non-synchronous generators in power station work. Obviously the disadvantage of the non-synchronous generator for power station work is, that it cannot carry a lagging wattless current, that it requires an additional lagging wattless current to excite it. The power-factor of the current supplied by such a generator is a direct measure of the amount of wattless current required to excite it under that particular load. The power-factor which can be obtained in designing any non-synchronous generator, depends on the size, speed, voltage, and frequency of the machine. Low speed, high voltage, and high frequency, all tend to lower the power-factor which can be obtained.

Table 1 gives the characteristics of steam-turbine and gas-engine-driven non-synchronous generators of from 1000 kw. to 10,000 kw. for 2200 and 13,200 volts, and for 25 and 60 cycles. The table shows that on high-speed 2200-volt generators, the power-factor rises as high as 98.25 per cent. and that we can obtain on such machines a power-factor which averages 97% to 98% from one-half to one and one-quarter load, while the no-load magnetizing current is less than 10% of the full-load current of the machine. This being the case, the fact that these generators require a wattless current to excite them, ceases to be a serious objection, and it is seen that the one important limitation of this type of machine is, that it cannot supply lagging wattless current to the outside circuit. Of course the low-speed, 60-cycle machines, are relatively poor as regards power-factor and exciting current, so that the use of non-synchronous generators would not be advocated under these conditions, unless their other characteristics made them particularly advantageous for the conditions under which they were to be used. It will also be seen from Table 1 that another advantage of this type of generator, is the extremely high efficiency at all loads that is obtained in high-speed machines. This means that these generators have a very low temperature rise at normal rated load, and that they have a very large overload capacity. The normal ratings of the individual machines given in the table were chosen so that their characteristics would be best at from one-half to one and one-quarter rated load. All the machines given, can generate from two and one-half to five times their rated output, and as far as general characteristics are concerned could be rated up 50%. It was stated above that the slip of the non-synchronous generator relatively to the synchronous generator, must increase from no load to full load, in order that the former may carry its due share of the load. So if we wish the load always to be automatic-

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ally divided between the two machines, we must adjust the governor of the synchronous prime-mover so that its drop in speed from no load to full load, equals the drop in speed of the non-synchronous prime-mover plus the full-load slip of the non-synchronous generator. This means that the speed and frequency

TABLE I

25 Cycle—Turbo-Alternators

Kilo-watts	Rev. per min.	Volts	Efficiency			Power-factor			No-load current	Slip
			1	0.75	0.50	1	0.75	0.50		
1000	1500	2200	97.6	97.7	97.5	97.0	97.5	97.0	8.3%	0.75%
		13000				95.0	95.9	96.5		
2500	1500	2200	98.2	98.2	97.9	97.9	97.3	96.4	8.3	0.48
		13000				96.5	96.9	96.0		
5000	1500	2200	98.3	98.2	98.0	98.0	97.7	97.4	8.5	0.46
		13000				96.5	97.0	96.5		
10000	750	2200	98.5	98.4	98.2	98.2	98.0	97.5	8.1	0.40
		13000				96.8	97.3	97.1		

60 Cycle—Turbo-Alternators

Kilo-watts	Rev. per min.	Volts	Efficiency 1	Efficiency 0.75	Efficiency 0.50	Power-factor 1	Power-factor 0.75	Power-factor 0.50	No-load current	Slip
1000	1800	2200	97.6	97.7	97.5	96.4	96.9	96.4	9.5	0.75
		13000				94.0	95.0	94.5	11.5	
2500	1800	2200	98.2	98.2	97.9	97.2	96.8	96.2	9.5	0.48
		13000				94.5	95.3	94.8		
5000	1200	2200	98.3	98.2	98.0	96.0	97.2	97.0	9.5	0.45
		13000				94.5	95.6	95.5		
10000	720	2200	98.5	98.4	98.2	97.6	97.6	97.1	9.5	0.40
		13000				95.3	95.6	95.5		

25 Cycle—Gas-Engine-Driven Alternators

Kilo-watts	Rev. per min.	Volts	Efficiency 1	Efficiency 0.75	Efficiency 0.50	Power-factor 1	Power-factor 0.75	Power-factor 0.50	No-load current	Slip
1000	94	2200	96.7	97.1	97.2	94.0	94.2	92.0	16.5	1.5
		13000				89.3	90.9	88.7	18.0	
2000	83	2200	97.0	97.4	97.6	95.5	95.1	94.0	16.5	1.4
		13000				92.4	93.2	90.7		
3500	75	2200	97.1	97.5	97.7	95.7	95.2	94.2	16.5	1.4
		13000				92.6	93.4	91.0		

60 Cycle—Gas-Engine-Driven Alternators

Kilo-watts	Rev. per min.	Volts	Efficiency 1	Efficiency 0.75	Efficiency 0.50	Power-factor 1	Power-factor 0.75	Power-factor 0.50	No-load current	Slip
1000	3	2200	95.5	95.7	96.0	88.8	88.5	84.6	25.0	1.8
		13000				83.0	81.	73.3	40.0	
2000	82	2200	96.0	96.3	96.5	89.5	89.2	85.6	24.0	1.7
		13000				83.5	81.8	75.0	38.0	
3500	75	2200	96.3	96.5	96.7	90.8	89.5	87.0	22.5	1.6
		13000				85.0	83.3	77.0	35.0	

of the synchronous generator must change with the load, but we see from the slip given in the table that this change is unimportant. The slip varies from 0.4 per cent. to 0.75 per cent. in high-speed machines and from 1.4 per cent. to 1.8 per cent. in low-speed machines, and this is about as close as the governors will regulate in any prime-mover.

The greatest commercial field for the non-synchronous generator, is undoubtedly in connection with turbine-driven generators. This type of generator is more suitable both mechanically and electrically for high-speed work than any other type of electrical machine. The squirrel-cage secondary with heavy copper bars, each bar held in a separate closed slot, and practically requiring no insulation, is an ideal construction mechanically, and is one which can be operated at very high temperature without damage. Comparing this with the rotating magnets of the standard synchronous turbo-alternator, the difference is very great. The magnet winding of a synchronous turbo-alternator consists of a number of turns of thin strap separated by insulation. The windings often reach high temperatures due to overload at low-power-factors, and are subject to heavy centrifugal stresses and a potential difference of 125 volts to ground. We can see that such a construction does not compare with that of the squirrel-cage rotating secondary of a non-synchronous generator. And as a break-down on the field of a synchronous turbo-generator usually puts the machine out of commission for a couple of weeks, we can see the mechanical advantages possessed by the non-synchronous generator. The simplicity in construction and insulation of the rotating parts, the ease with which the centrifugal stresses necessarily present can be taken care of, and the absence of a complicated winding and brush gear, necessarily tend to reduce the cost of the machine compared with that of the standard synchronous generator. Of course the actual cost of any machine depends on the performance specification to which it is designed, and on how closely the machine is rated, but it can readily be seen that the non-synchronous generator offers facilities for cheaper design and manufacture which are not presented by the synchronous generator.

The excitation of the non-synchronous generator. A synchronous generator requires direct-current excitation, while a non-synchronous generator requires alternating excitation. The non-synchronous generator is excited by a lagging current taken usually from a synchronous machine, and as this synchronous machine requires direct-current excitation to produce this lagging current, it can be said that indirectly the non-synchronous generator does require a direct-current exciter. But on account of the small air-gap of this type of generator, it requires much less excitation than a synchronous generator. The actual capacity of the exciters which are required by a power station consisting of non-synchronous generators, depends on the power-factor of the load on the system. The capacity required will usually vary from one-quarter to one-half of that which would be required for the corresponding synchronous generators. Of course if we have a cable system with high electrostatic capacity, this will supply part of the required lagging excited current and will reduce the size of the required exciter. The charging current of the New York Interborough system is about 105 amperes at 11,000 volts; that is, about 2000 kilovolt-amperes, and that of the New York Edison system is about 40 amperes at 6600 volts; that is, about 450 kilovolt-amperes. We see from Table I that the capacity-charging current of the New York Edison system is sufficient to supply full-load magnetizing and wattless current required by a 2000-kw. 6600-volt, 25-cycle turbo-driven non-synchronous generator when running on a non-inductive external load. In the same way the capacity-charging current of the Interborough system would be sufficient to supply the wattless current of a 10,000-kw. 11,000-volt, 25-cycle turbo-driven generator. If we had a cable system such as the Interborough distributing at 20,000 volts, we would have a charging current of 190 amperes at 20,000 volts, which would be sufficient to supply the wattless component for 40,000 kw. in 22,000-volt, 25-cycle turbo-driven non-synchronous generators. So we can see that the electrostatic capacity of a large cable system will play an important part when we come to consider the introduction of such generators into some of the large New York power stations.

In a system consisting of non-synchronous generators supplying power to synchronous converters, it is unnecessary to have any exciters or synchronous machines in the power station. The first converter put in circuit, must be run up to speed from the direct-current side, and then thrown into the generator circuit, when it will excite the latter, and the voltage will be decided by the excitation of the converter. We can see from Table I that the power-factor of a non-synchronous generator can be made to remain practically constant from one-half to one and one quarter load. This means that the amount of wattless lagging current taken by the generator throughout its normal working range, will be practically proportional to the watt current. Hence assuming that we can neglect the capacity-charging current of the cable system, if we have a number of converters running in the circuit, we can adjust the shunt excitation of each converter so as to give the correct voltage at no load, and the series excitation can be adjusted to obtain any desired voltage-characteristic as the load comes on the system, the converters compounding the generators by their series winding. This compounding of the generators as the load comes on any sub-station, affects of course all the other sub-stations fed from those generators; so if we are not regulating for constant voltage, it may be advisable in some cases to introduce artificial self-induction into the converter feeder circuits so as to over-compound the converter feeder circuits rather than the generators, and avoid disturbing the voltage on other unloaded sub-stations. In a large system, the capacity current of the cables can not be neglected, so the wattless current to be supplied by the converters will not be directly proportional to the load. Such a system usually requires constant voltage at the direct-current terminals, and in such cases it may be found advantageous to install compound-wound converters with automatic voltage regulators to control the shunt excitation. The voltage regulators would then serve to control the voltage of the generators, and to keep that constant, while the series winding would serve to compound each individual feeder in order to compensate for the voltage-drop in that feeder. In such a system, all the regulators controlling the voltage on a given group of generators would be tied together, so that any one regulator could not act before, or act against the others, and make the shunt excitation of the individual converters different.

If there is no electrostatic capacity in the system, the power-factor of the converters is practically the same as the power-factor of the generators; but if there is capacity in circuit which helps to supply the lagging current, then the power-factor of the converters will be higher than that of the generators. Taking once more the Interborough system, and assuming there are 75,000 kw. of 11,000-volts turbo-driven non-synchronous generators in the power station, and 75,000 kw. in synchronous converters in the sub-station, then the capacity current supplies 13 per cent. of the wattless current taken by the generator on full load, and we have a full-load power-factor for the converters of 98 per cent. Such a power station of non-synchronous generators, having no direct-current exciters and exciting circuits, is much simpler as regards cables and switchboard connections than a similar station with synchronous generators, and is much simpler to operate. There is no necessity for synchronizing the generators; they are simply run up to speed and are then thrown on the line in series with a reactive-coil, (to limit the rush of current). The reactive coil is then short-circuited, and the generators are automatically excited from the converters and take care of themselves. The governors of the prime-movers are controlled by pilot motors from the switchboard, and the load can be distributed at will among the different generators without adjusting the excitation to keep the power-factor constant, as would be necessary with the synchronous generator. This gives an ideally simple station, as there are no auxiliary circuits, and the switchboard is practically limited to the main generator and feeder switches and instruments.

Short-circuits and resonance. During the last few years we have heard a great deal regarding resonance and high power surges in large installations with distributing cable systems of high electrostatic capacity. We can investigate these phenomena mathematically in detail, if we choose to make a number of more or less arbitrary assumptions, but it is the author's opinion that at present we are only justified in describing these phenomena in general terms. By a high-power surge is meant the oscillation sometimes set up in a system by a sudden rush of current, such as a short-circuit, and which has usually the fundamental frequency of the circuit. The power represented by the surge, is proportional to the square of the value reached by the current in the first sudden rush, and the rise in voltage is directly proportional to the surge of the current. Resonance effects, cover the extremely high rises of potential which take place in a circuit containing self-induction and capacity, when the frequency of the circuit has a certain value depending on the amount of induction and capacity in circuit. In ordinary power systems, resonance cannot generally take place at the normal frequency of the circuit, but there are usually higher harmonics of this normal frequency introduced by distortion of the fundamental wave-form, and there may be resonance and high voltage due to one of these high harmonics.

This short analysis shows at once why a power station of synchronous generators, is so liable to suffer from surges and resonance. Synchronous generators and motors will give a greater sudden rush of current, or surge, in the case of short-circuit than almost any other class of machine. And though they have wave-forms which approximate closely to sine waves on no load, these wave-forms become so distorted by armature reaction on load, and change so with the magnitude and phase of the current, that there is an excellent chance of introducing such harmonics as will produce resonance. If we were deliberately to try to choose conditions which would be most liable to give trouble from high-power surges and resonance, we could not well choose anything that would be worse than synchronous generators feeding synchronous motors through a cable system of high capacity. The non-synchronous generator is a great contrast to the synchronous generator in this respect, as it tends rather to eliminate disturbances from the line than to originate them.

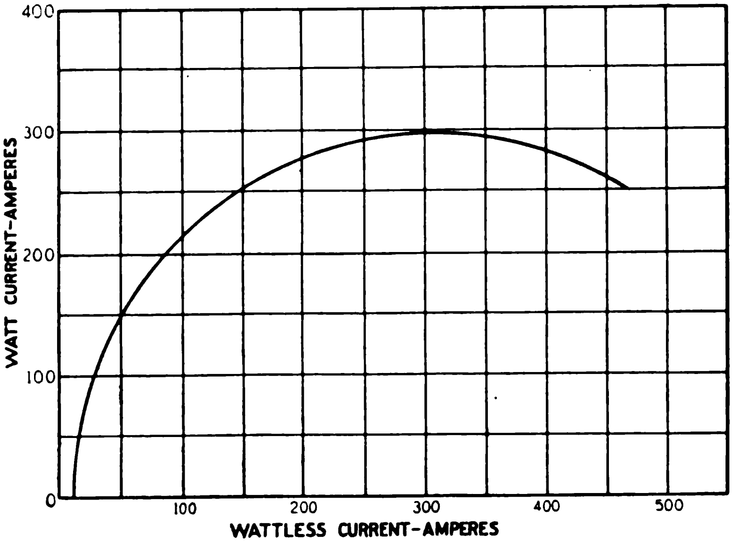

Fig. 1.

A short-circuit on a system means that the voltage falls to zero, consequently any non-synchronous generator on the circuit becomes dead, and does not tend to supply either power, current, or voltage to the short-circuit. Further, the wave-form of the electromotive force of a non-synchronous generator is virtually a sine wave for all loads, and it has no tendency at all to introduce higher harmonics which might produce resonance. If the synchronous machines supplying the wattless current in the circuit have a badly distorted wave-form, the magnetizing current of the non-synchronous generator will also be distorted, but there will be a strong tendency to damp out all harmonics in the electromotive force wave-form of the system. And we can say that, generally speaking, the non-synchronous generator acts as a strong damper to remove all harmonics in the electromotive force wave-form of the system, introduced by distortion of the wave-form of the synchronous machines. This distortion in a synchronous machine, is due to the armature reaction of the watt component of the current, rather than the wattless, so we see that the best conditions as regards freedom from distortion and harmonics are obtained by the use of a synchronous converter or unloaded synchronous machine, rather than a loaded synchronous generator or motor to supply the wattless current required to excite a non-synchronous generator.

Fig. 1 shows the relation of the watt component to the wattless component of the current supplied by a 2000-kw. non-synchronous generator, the curve being for its normal rated voltage of 11,000 volts; for a different voltage the values of current, both watt and wattless, should be multiplied by the direct ratio of the new voltage to 11,000 volts. We can see from this, that the magnitude of the watt current bears a definite relation to that of the wattless, and that the watt current, and consequently the load on the machine, cannot change without the wattless current also changing. Further, for each point on the curve, the slip of the non-synchronous generator ahead of the synchronous machine has a *certain definite* value. This shows that when a short-circuit comes on a system consisting of a non-synchronous generator and synchronous generator or motor, the short-circuit will come on the synchronous machine. If the voltage drops to zero, the non-synchronous generator will be dead; but if the short-circuit is not severe enough to reduce the voltage of the system to zero, then it may still supply current to the circuit. The amount which it supplies will depend on the way in which the excitation of the synchronous machines is changed by the automatic voltage regulators. But a change in load which can be taken care of by the voltage regulators, hardly comes under the class of short-circuits, and as these latter effects are the only serious ones, we will consider them alone. We see from the above that the non-synchronous generator takes no part in the sudden surge of current which occurs on a short-circuit, so that this surge cannot be greater than that which is supplied by the synchronous machines in circuit. The sudden surge which takes place when any synchronous machine, whether generator, motor, or converter, is short-circuited is equal to:

Electromotive force of synchronous machine
self-induction in circuit

After the current has flowed for an appreciable time, so that the magnetism of the synchronous machine has had time to change, the armature reaction cuts down the electromotive force generated, and the current falls to the value commonly known as the short-circuited value, this being the value of the current on a continuous short-circuit. The 5000-kw. 11,000-volt Manhattan generators will give a continuous short-circuit current about three times full-load current, but the instantaneous value of the current on a sudden short-circuit is about five times this; that is about fifteen times normal full-load current. If these generators are supplying synchronous converters, these converters will also supply power to the short-circuit. The 1500-kw. Manhattan converters give about full-load current on a continuous short-circuit on the alternating-current side, with the self-induction of the transformers and reactive-coils in circuit, and the instantaneous value on sudden short-circuit is about three times this value. So a short-circuit on a system consisting of the Manhattan generators supplying power to synchronous converters will give, on sudden short-circuit, a rush of current equal to eighteen times the total full-load current of the generators in circuit, while after a short period the value of the short-circuit current will fall to about one-fifth of this value. Assuming now that we had non-synchronous instead of synchronous generators in the power station, the short-circuit current would be limited to that from the converters, and the sudden surge would be equal to three times full-load current. The voltage of the system would fall to zero, and the converters would supply a gradually decreasing current to the short-circuit until their rotational energy was all expended, and they had come to rest. We see then that with non-synchronous generators in the power station, the magnitude of the sudden surge on a short-circuit would be reduced to one-fifth of that which would take place with the present synchronous generators. This means that the voltage-rise would be only one-fifth, and the power of the surge would be only one twenty-fifth. These figures do not need any comment.

There is one point, however, that must be considered when operating non-synchronous generators on the system containing considerable electrostatic capacity, and that is that the individual generator units are not too small. A non-synchronous generator can be excited by the lagging current from a condenser, and the voltage to which it will be excited depends on the size of the condenser. In a system consisting of non-synchronous generators and synchronous machines we might, as the result of opening circuit-breakers by line disturbances, have just one generator and one small synchronous unit left running on the line. The capacity current of the cable system would then tend to build up the voltage of the machines until the saturation of the magnetic circuit prevented any further rise. Taking the 2000-kw. 11,000-volt non-synchronous generator, the current curves of which are shown in Fig. 1, the magnetizing current at 11,000 volts is nine amperes. If the capacity-charging current of the cables is 100 amperes at 11,000 volts, and the synchronous machine is so small as to take a negligible lagging magnetizing current, it would probably mean that the voltage of the machines would build up to double the normal. If, however, the smallest machine on the circuit were a 10,000-kw. generator, a 1500-kw. synchronous motor or synchronous converter, the rise in voltage would not be more than 10 per cent.; if the minimum size generator unit had been 20,000 kw. there would be no rise in voltage; so that this is a condition which can be taken care of when laying out the station.

Distortion of the wave-form introduces higher harmonics, and may cause resonance or cross-currents. In a synchronous generator or motor, the wave-form of the magnetism is usually badly distorted as the load comes on the machine, this distortion being greater the higher the power-factor, and the greater the load. This distortion of the magnetic wave, introduces higher harmonics into the wave-form of the electromotive force generated in the armature conductors. The most important harmonic introduced is the third; but the fifth, seventh, ninth, and higher harmonics are also usually presented. In a three-phase winding, the third harmonic, and also harmonics of this third harmonic, appear in the electromotive force between the neutral and outer terminals, but not in the electromotive force between the outer terminals. They therefore appear in a three-phase, four-wire system or in a three-phase system with grounded neutral. The other harmonics appear, no matter what the connections are. Though the presence of these harmonics may not cause harm in any individual case, it is always possible that there may, under certain conditions of circuit and load, be harmonics of a frequency sufficiently close to that of resonance to cause serious rise of potential. And if generators of different characteristics run together, or if there are loads of different magnitude and phase, or there is different excitation on the synchronous generators or motors, cross-currents are liable to be produced between the machines; this is especially the case in running with a grounded neutral. Synchronous converters are very much better than any other class of synchronous machines as regards distortion of wave-form when operating with unity power-factor; they have practically no armature reaction, and the electromotive force wave generated under such conditions is approximately a sine. So the above remarks on synchronous generators and motors, only apply to synchronous converters to a limited extent.

Non-synchronous generators have no distortion of field due to armature reaction, and so long as the iron in the magnetic circuit is not saturated, the electromotive force wave-form of these generators is virtually a sine wave for all conditions of load. This means that there can be no cross-current between non-synchronous generators, and that they have no tendency to produce resonance in the circuit. Furthermore a non-synchronous generator acts as the strongest possible damper in a circuit; and if there is any surge, unbalancing of phases, distortion of wave-form or hunting present. the non-synchronous generator will tend to damp it out, and to restore the original condition of steady sine-wave operation. If we then have a system consisting of non-synchronous generators supplying power to synchronous converters, it would be as nearly perfect as possible in its freedom from surges and resonance. The synchronous converter would give the minimum distortion of any synchronous machine, and the non-synchronous generator would tend to damp out any disturbance that occurred on the line. Such a system would certainly be very much superior to the synchronous generators and synchronous motors in regard to liability to disturbances from resonance and surges, and in all probability the engineers of such a system operating with grounded neutral would hardly know that such phenomena existed.

I have endeavored to show that the non-synchronous generator is very much superior to the synchronous generator from almost every point of view, for the purpose of supplying power to motor-generators and synchronous converters through an underground cable system; and that synchronous converters are less liable to introduce line disturbances than synchronous motors. In some cases it might be considered advisable to install both synchronous and non-synchronous generators, or the station might be one in which the units first installed were synchronous generators, and the later extensions were non-synchronous generators. In such cases it is readily seen that the advantages as outlined above, are obtained to a degree which depends on the ratio of the number of non-synchronous to the synchronous generators. It should be remembered that the non-synchronous generator and synchronous converter, give the best combination to ensure freedom from line disturbances, and that the synchronous generator and synchronous motor give the worst; combinations of the two systems lie between these two.

Small power stations. There have now been considered in detail, large systems which can easily provide the necessary lagging exciting current for the non-synchronous generator, either from the charging current of the cable system or from the synchronous motors or synchronous converters in the system.

With smaller power stations which supply power direct to motor and lighting circuits, the conditions are not so favorable to the non-synchronous generator, as this generator is primarily one for high power-factor loads, and it is at a distinct disadvantage in a station in which the load is of low power-factor. The advantages of the non-synchronous generator as outlined above are, however, so great that each particular case should be considered to see whether it will allow of its use. Usually the load on such a station having low power-factor, consists mainly of motors during the day time, whereas the heavy peak load is the lighting load at night. We can therefore install synchronous generators sufficient to carry the day motor load, and non-synchronous generators to assist in carrying the lighting load at night. Let us take a 60-cycle station with a day load of 2500 kilovolt-amperes which will probably have a power-factor of 70 per cent. and a night load of 4000 kilovolt-amperes with a power-factor of 98 per cent. And assume further that we have two 1250-kilovolt-amperes synchronous turbo-generators to carry the day load, and two 1000-kilovolt-ampere non-synchronous generators to assist in carrying the night load. This night load consists of 3850 watt kilovolt-amperes and 800 wattless kilovolt-amperes, and the two non-synchronous generators require in addition 980 wattless kilovolt-amperes to excite them. We shall then have the two synchronous generators carrying a load of 2500 kilovolt-amperes at 70 per cent. power-factor and the non-synchronous generator carrying a load of 2250 kilovolt-amperes at power-factor 0.98.

It is nearly always more economical to supply wattless current in a power station from unloaded high-speed synchronous motors, than from the main synchronous generators. This is more especially the case with steam-turbine or very slow-speed units, as such machines cannot be economically designed with the good regulation and the margin on the fields necessary to handle properly a low power-factor load. Such a machine to carry satisfactorily a certain kilowatt load at power-factor 70 per cent. will be about double the size of a unit to carry the same kilowatt rating at unity power-factor, 1. In the station considered, we have assumed that the synchronous generators supply all the wattless current required for the non-synchronous generators and outside circuit. It would be better, however, to make the synchronous generators 1000 kilovolt-ampere units with poor regulation, and install also a 1500-kilovolt-ampere high-speed synchronous motor to supply all the wattless current. This should give a cheaper and more flexible installation, as we would be able to run the non-synchronous generators without the synchronous generators at any time, using the synchronous motor to excite them. The non-synchronous generators would require no direct-current exciters, exciting circuits, or switch panels: they would probably be cheaper than the synchronous generators, and would be simpler to handle, and less liable to break down. So we can see they have such important advantages that they should be carefully considered in each individual case before deciding to adopt synchronous generators alone.

Other applications of non-synchronous generators. In the above remarks, the non-synchronous generator has been dealt with more especially as a steam-turbine-driven unit for generating alternating current. This type of generator, however, often presents important advantages for other and more especial conditions. Two of the most important of such cases are gas-engine-driven alternators, and steam-turbine-driven direct-current units. The advantage of the non-synchronous generator for gas-engine-driven units, is of course that it does not require the extreme uniformity of speed required by a synchronous generator, and the advantage of its application for direct-current generation by turbine units is, that by the use of a non-synchronous generator and synchronous converter we can avoid the use of a direct-current turbo-generator.

Gas-engine-driven units. With the modern tandem and twin-tandem gas engines, giving respectively two and four impulses per revolution, gas-engine-driven alternators can undoubtedly be run in parallel. But to obtain the same kind of satisfactory operation that is obtained with steam engines, enormous fly-wheels and heavy dampers on the pole-faces of the alternators are necessary. Such fly-wheels mean a considerable increase in cost, and sometimes in the floor space taken up by the engine, and also a loss in efficiency due to the increased bearing friction and windage. And there is necessarily a considerable loss in the dampers on the pole-faces of such a gas-engine-driven alternator, because the irregularity of speed in a gas engine is such compared with that obtained in a steam engine, that the dampers have to perform heavy work in accelerating and retarding the fly-wheels. We can readily see that there can be easily an increased loss of three per cent. to five per cent. from these two causes, which would not be detected except in a gas-consumption test, when running in parallel with other units. Instead of synchronous units, we can install non-synchronous generators and have high-speed synchronous motors running light, to provide the necessary lagging current for the outside circuit and for exciting the generators. In this case any change in load comes first on the synchronous motors, causing a change in their speed, and in consequence a transferring of the change in load to the generator. And as the voltage of the generator would be decided by the excitation of the synchronous motors, the voltage regulation of the station is that of the synchronous motors. Hence for constant potential it may be advisable in some cases to control the excitation of all the synchronous motors by one automatic voltage regulator. The size of the direct-current exciter necessary for the synchronous motors would depend on the power-factor of the load on the station, and would be greater, the greater the lagging current required by the external circuit. Generally speaking, the size of the exciter required, would be from one-quarter to one-half of that necessary for the corresponding synchronous generators. The probable arrangements would be, a direct-connected exciter on each synchronous motor, which could also be used as a starting motor; and one gas-engine-driven exciter would also have to be installed for starting up the first synchronous motor.

Taking as the load on such a 2200-volt, 25-cycle power station, 20,000 kilovolt-amperes at 70 per cent. power-factor, we would have from 5000-kilovolt-amperes, 75 rev. per min. synchronous generators, each requiring a 125 kw. exciter; or from 3500-kw. 75 rev. per min. non-synchronous generators, together with from 4500-kilovolt-ampere 500-rev. per min. synchronous motors with 60-kw. direct-coupled starting motor-exciters. Each synchronous motor would supply the 1000-kilovolt-amperes exciting current required by one non-synchronous generator, together with 3500-kilovolt-amperes wattless current for the external circuit. The relative efficiencies on the load of 70 per cent. power-factor are as follows:

	Synchronous generator	Non-synchronous generator and synchronous motor
Full load	95.7—(a)	94.0
0.75 "	95.1—(a)	93.6
0.50 "	94.0—(a)	92.5

These efficiencies do not take into account the allowance (a) to be made for additional losses due to the increased friction of the larger fly-wheels, and the losses in the dampers or solid pole-faces which occur with the gas-engine-driven synchronous generator. These additional losses will reduce the efficiency of the synchronous generator below that of the non-synchronous generators set. The cost of the electrical equipment would not be very different in the two cases. and as the larger fly-wheel shaft and bearings required for the synchronous generator would increase the cost considerably, it is probable that the non-synchronous generator equipment would be found a good deal the cheaper. It must be remembered that this is an extreme case, because the low power-factor of 70 per-cent. taken for the outside load is very much against the non-synchronous generator. If the power-factor were higher, the result would be much better.

It might be supposed that unless we had very heavy fly-wheels on the gas engine we would have the same trouble with hunting of the non-synchronous generator and synchronous motor that we would have with the synchronous generator. But such is not the case. There will undoubtedly be cross-currents between the machines, the magnitude of which will depend on the variation in the speed of the gas engine, but it will be practically impossible to break them out of step. The worst effects of this interchange of current between the machines, will be the heating and losses in the armature conductors, and the pulsation in voltage due to the interchange of wattless current. This pulsation of voltage will be diminished by dampers on the pole-faces of the synchronous motor, but it will usually be perceptible when only one generator is running. As these gas-engine-driven units will be used mainly for power work in mills, the slight pulsation of voltage will be unimportant.

Non-synchronous generators are not put forward as the only possible solution of the gas-engine-driven alternator question; but as the most practical, and that which will recommend itself most highly to the conservative power station engineer and manufacturer. It is by no means settled that extremely heavy fly-wheels and powerful dampers are a practical, and advisable solution of the parallel running difficulties.

Steam-turbine-driven direct-current units. The other special case for the use of the non-synchronous generator above referred to—the use of such a generator, together with a synchronous converter for the production of direct current—is to meet the special case in which a steam turbine is desired as a prime-mover. Reasons which might compel the choice of the steam turbine are numerous: small overhead space, small floor space, poor foundations, objection to the vibration of reciprocating engines, high steam economy required over a wide range of loads, reduced maintenance and supervision—all these might influence the choice of prime-mover. And as the direct-current turbo-generator, particularly for 250 and 125 volts, has as yet hardly established its position as a conservative and reliable machine, some kind of alternating-current generator would be used in combination with a motor-generator or synchronous converter. Two years ago an electric railway and light company, wished to install an auxiliary 3000-kw. 300-volt direct-current steam-driven generating equipment in the basement of their new public service building. As the head-room was limited to about 12 feet, and as the vibration would be objectionable, reciprocating engines were out of the question. They installed two 1500-kw. horizontal steam-turbine-driven synchronous alternators, and two synchronous motor-generator sets. This would have been an ideal case for a non-synchronous generator and synchronous converter. The converters could be started from the direct-current system, and when up to speed would have excited the non-synchronous generators; no exciters nor exciting circuits would be necessary, the voltage being controlled by the excitation of the converters. The equipment installed, has a combined full-load efficiency of about 86 per cent. while the combined efficiency of a non-synchronous generator and synchronous converter to do the same work, would have a full-load efficiency of about 95 per cent. In addition it would probably have cost about one-third less.

In comparing a turbine-driven non-synchronous generator and synchronous converter, with a steam-engine-driven direct-current generator, the former is found to be a more flexible equipment, one which will carry heavier overloads, and is usually cheaper. We can obtain any compounding desired by means of a compound winding on the converter, and by use of transformers we can have converters of different voltages to supply different direct-current systems. We can place the converter at a distance and transmit the power to it at a high voltage, or we can split up or arrange the equipment as we please. The efficiency is slightly higher on the non-synchronous generator equipment than on the engine-type, as can be seen from the following table of full-load efficiencies for 270-volt generators.

	1000 kw.	2000 kw.	3000 kw.
1. Non-synchronous generator	97.5	98.0	98.25
2. Synchronous converter	97.0	97.5	97.75
3. Combined efficiency of non-synchronous generator and synchronous converter	94.5	95.5	96.0
4. Engine-type	93.5	94.25	94.5

There are many indications that the day of the large engine-type direct-current generators is past. The inaccessibility of the brushes, the difficulty of building and maintaining a commutator of large diameter, and the numerous other drawbacks of this type of machine, have caused it to be regarded as an undesirable addition to a power station. It is a question whether the non-synchronous generator and the synchronous converter are not superior to the engine-type direct-current generator in almost every case, and it should always be carefully considered when a new direct-current station is laid out, or when any extensions are added to existing plants.

I have endeavored to show that the one great disadvantage of the non-synchronous generator—its inability to carry a lagging wattless current load—should not always prevent its successful adoption. And that the important advantages it possesses; its excellent mechanical construction, high efficiency, good characteristics in regard to short-circuits and resonance; strong balancing and damping action, absence of rotating windings or collector rings, absence of direct-current excitation and exciting circuits, ease of parallel running, facility for.control of load by governoı, and general simplicity and flexibility of operation—all these make it in many cases by far the most advisable machine to adopt. The non-synchronous generator suffers from the fact that it was judged and condemned in the early days of electric power generating stations. At that time there was no real field for this generator, but the introduction of steam turbines and gas engines, and the modern development of large power stations have so fundamentally altered conditions, that the non-synchronous generator is no longer an interesting curiosity, but one of the most promising types of generator for power station equipment. The record of three years in service, places this machine on a demonstrated commercial basis, and while it may have limitations, it possesses so many advantages and its sphere of usefulness is so large, that in the opinion of the author it must be acknowledged to offer greater future possibilities than almost any other type of power station equipment.

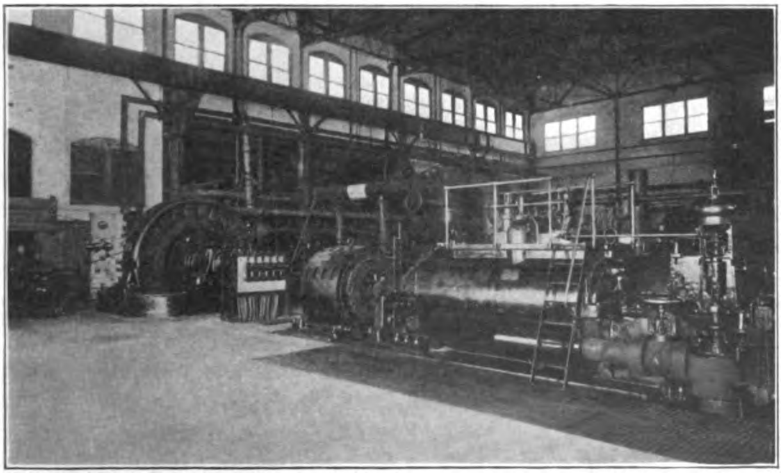

FIG. 2

APPENDIX.

The following data on the steam consumption obtained from tests in the copper smelting and rolling plant referred to earlier in the paper, are of interest in comparing the efficiencies of the two types of direct-current generating equipment. The first column gives the actual steam consumption of the 1200-kw. steam-turbine-driven non-synchronous generator and synchronous converter, the turbine being run with 140 lb. steam pressure, 28 in. vacuum and 135 degrees superheat. The second column gives the corresponding figures on a Corliss engine and direct-connected generator, the steam consumption being based on a minimum consumption of 12.5 lb. per indicated horse power at 80 per cent. of full load.

Pounds of steam per kilowatt-hour at direct-current terminals

Load	Steam turbine equipment	Corliss engine equipment
0.5 load	21.2 lb.	23.5 lb.
0.75 "	18.2	19.8
1. "	17.5	20.3
1.25 "	17.5	23.2

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SOME DEVELOPMENTS IN SYNCHRONOUS CONVERTERS

BY CHARLES W. STONE

It is not the intention to make this paper a history of the development of the synchronous converter, but rather to point out some of the more important improvements which have been made in the last few years.

In this country the synchronous converter has become practically an indispensable piece of apparatus, some of the largest lighting and railroad companies being entirely dependent upon it. Abroad the conditions are different, as the motor-generator has been used almost exclusively until within the last few years, when the motor converter was introduced; as is well known, this machine being a compromise between the synchronous converter and the motor-generator.

It may be of interest to give at this time some idea of the increase in capacity of these machines in the last ten years on one of the large lighting systems, as this will give some idea of the tremendous development in machines of this type. In 1897, on the particular system in question, there was installed less than 1000 kw. total capacity, and the largest machine was 500 kw.; on the same system in 1907, considerably over 100,000 kw. in operation, were the largest units being 2000 kw.

Most of the larger systems using synchronous converters operate at 25 cycles, but during the last four or five years many systems using 60 cycles have adopted synchronous converters and have found them very reliable.

I think it can be safely said that 60-cycle synchronous converters, even when used for 600-volt railway work where the demands of the service are most severe, can be considered thoroughly reliable and successful, machines as large as 1500 kw. being in successful operation.

The general tendency in the design of synchronous converters has been toward higher speeds, which would naturally mean reduction in the space occupied by them, lower first cost, less weight etc. All these changes result in smaller buildings, cheaper foundations, and consequently lower fixed charges.

As an illustration of the changes that have been made, I shall cite one example. The 2000-kw., 25-cycle, 250-volt synchronous converter as originally designed, operated at 115 revolutions and had 26 poles. It occupied a floor space 190 in. by 204 in. and the total weight was approximately 186,000 lb., whereas the newer vertical machine is circular in form, the diameter being 182 in. and the total weight about 130,000 lb.

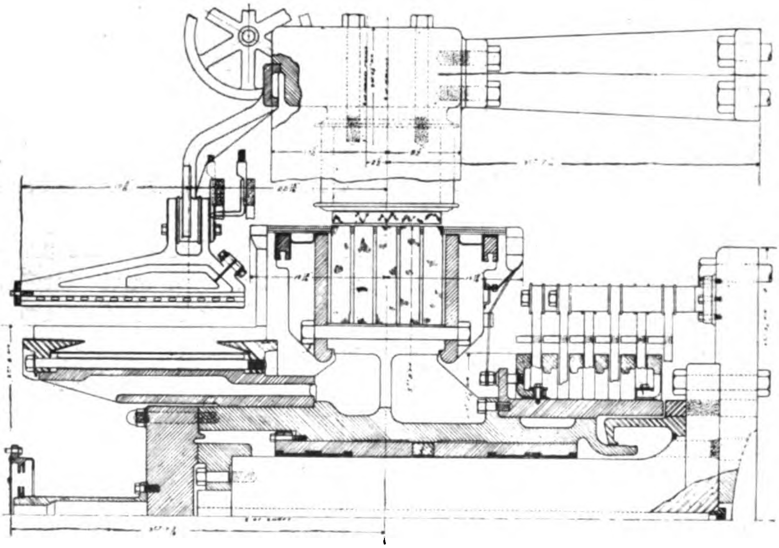

FIG. 1.

Vertical synchronous converters. The vertical synchronous converter is so new that it seems advisable to point out some of its essential characteristics. The most novel features are in the shaft and bearings. The shaft, unlike that of the horizontal machine, is stationary; in fact it is nothing but a pedestal supported and fastened solidly to the foundations. There is only one bearing, which carries the entire weight of the revolving structure. This bearing in the first machine built consisted simply of two cast-iron plates, one of which was fastened to the top of the pedestal and the other being bolted to the spider of the armature. Fig. 1, a cross-sectional view of the machine, shows more clearly this construction. Oil is pumped up through a central hole in the pedestal and forced out between the cast-iron plates, forming an oil film on which the machine revolves and making practically a frictionless bearing.

In addition to the main bearing, use is made of the entire length of the interior of the spider for a guide bearing. A cast-iron sleeve lined with babbitt is fitted into the spider to form the bearing surface. As the only weight on this bearing is that due to the unbalancing of the rotating structure, the bearing should last indefinitely. The oil after leaving the top or supporting bearing, passes along the pedestal, (thus oiling the guide bearing) down to the pocket at the base of the machine were it is drained off and used over again. Since the first machine was built, a new type of bearing has been tried which gives promise of success, although only a few months' experience has been obtained as yet.

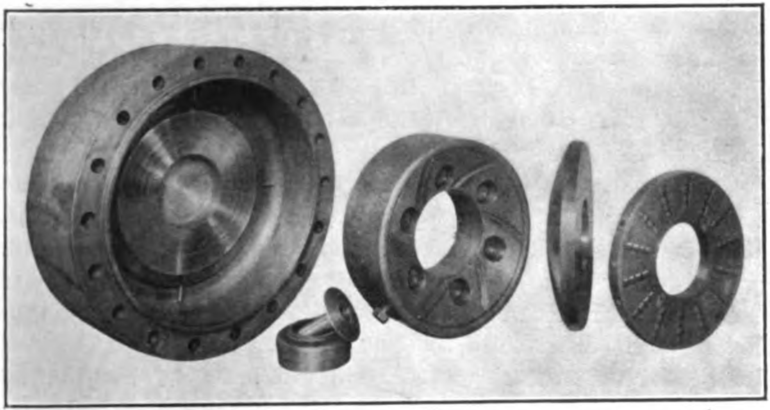

Fig. 2.

Fig. 2 shows in general the parts which are used to make up this bearing. The cup-shaped cast-iron piece shown in the cut is fastened to the top of the pedestal and forms a seat for the hardened steel bearing plate and carrier, the steel plate being simply doweled in place. Both sides of this plate are accurately ground so that it can be reversed in case of any damage to one surface. It can readily be seen that this construction of the two lower members of the bearing makes it self-aligning.

The top part of the bearing is bolted to the armature spider and is similar to the top of the oil-pressure bearing, except that another hardened steel plate is doweled in place on the under part of this casting to form the wearing surface. Between these steel plates is a bronze carrier with a number of hardened steel rollers placed radially, thus forming the roller bearing. Oil is pumped by a small low-pressure pump to this roller bearing and is drained off after passing through the guide bearing in exactly the same manner as with the oil step.

The stationary part carries the field spools and is split vertically so that the two halves can be drawn apart, making the armature accessible for inspection or repairs. This frame is supported on a number of cast-iron pedestals.

By the above construction it will be noted that the field frame is entirely independent of the rotating structure, making it easier to assemble the machine.

The armature being revolved around the pedestal, it is not possible to obtain any end-play, as in a horizontal machine. Some means must be provided to make the wear on the collector rings equal; this is accomplished by designing the brushes in such a manner as to make it possible to stagger them and thus cover the entire width of the collector rings. In addition there are placed on each ring some graphite brushes which act as lubricants.

Fig. 3 is an elevation of the first 2000-kw. machine of the vertical type which has been constructed in this country. By reference to this Fig. it is readily seen how accessible the machine is. It is possible to walk around the machine and see and adjust all the brushes on both the commutator and the collector rings without climbing up on a bearing pedestal or going down into a pit, as would be necessary in a large horizontal shaft machine. The bearings in the 2000-kw. vertical machine can be taken out, inspected, and replaced in a little over two hours, which would hardly be possible in a horizontal machine of the same size.

The construction above outlined makes it possible to build machines occupying minimum floor space; in fact it has been found possible in stations which have been laid out for 1000 kw., machines, horizontal shaft of the old type, to place a similar number of vertical machines of double the capacity.

Voltage regulation. The next matter is that of voltage regulation. With a synchronous converter, as is well known, it is not possible to regulate the direct voltage of the machine by means of the field rheostat, as is done with a direct-current generator, without changing the power-factor; for the ratio between the impressed alternating voltage and the direct voltage is fixed by the design of the machine. Hence where voltage regulation is necessary, as for lighting work, charging storage-batteries etc., some means of changing the impressed alternating voltage is necessary.

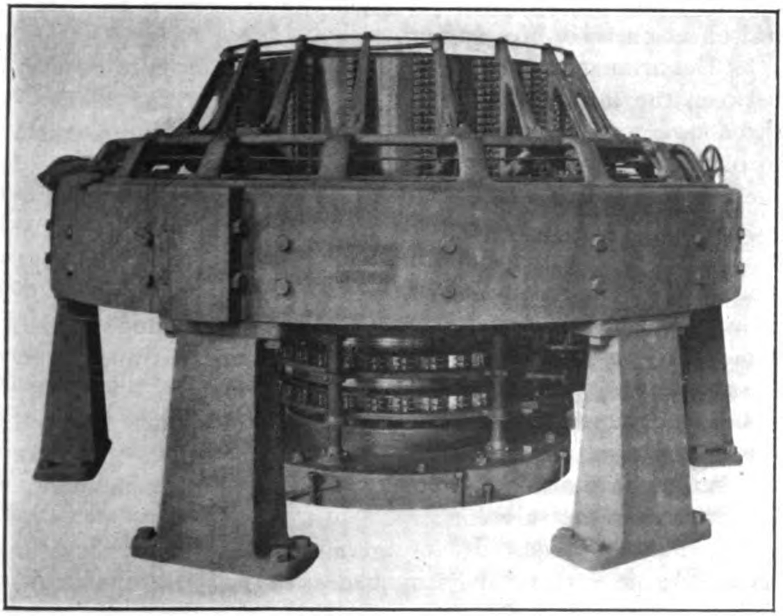

FIG. 3.

A number of different methods have been used to accomplish this result, which I will describe briefly:

1. On the step-down transformers used with the converter, taps can be placed either on the primary or the secondary side and switches used to transfer from one tap to another. This scheme has many objections and is seldom used now. If the taps are on the primary, oil-switches would have to be used if the voltage were at all high. Such switches would be practically out of the question. If the taps are on the secondary, a dial-switch

can be used but only with the smaller size machines, as it is difficult to build a dial-switch to handle large currents satisfactorily except at prohibitive expense. This method is also objectionable as it means fluctuation in the lights whenever the switch is moved to a different tap.

2. The common way of obtaining control of the voltage in railway work is to insert in the leads from the secondary of the transformer a reactance, thus causing an artificial drop in the impressed alternating voltage. This method, while simple and effective with the limited ranges in voltage required for such work, would not be applicable for large ranges in voltage. Too much reactance may cause pulsation troubles and it also has a bad effect on the entire system.

3. The arrangement in most general use to-day is to connect between the secondary leads of the transformer and the synchronous converter an induction regulator, by which it is possible to obtain almost any range of voltage within the capacity of the machine. This scheme of operation is in such general use that it will not be necessary to describe it in detail. The principal objection to this arrangement is that another piece of operating machinery is used with each synchronous converter outfit, increasing the cost, requiring valuable floor space, and making it necessary to open the secondary leads from the transformer, a complication with large low-voltage machines.

4. The next development in this line took place abroad, where an entirely different scheme was used. A few machines of this type have also been built by one of the large manufacturing companies in this country.

This method makes use of an alternating-current booster or bucker, mounted on the same base with the synchronous converter. The field has the same number of poles as the converter, and the armature is mounted on the same shaft as the synchronous converter armature. Alternating current is generated in this armature and can be made to add its voltage to or be subtracted from the impressed voltage according to the direction of the excitation. This booster is usually placed between the collector rings and the main armature of the converter, and the taps from the collector rings are connected to equidistant points of the booster armature; similar points on the booster armature are connected to the synchronous converter armature, thus placing the two in series, separate and distinct windings for each phase being used.

The principal objections to such an arrangement are that here again we have an additional operating machine, as in the case of an induction regulator. Extra weight is added to the shaft between its points of support. The ventilation of the converter armature and its accessibility are impaired. Any serious trouble with this smaller machine results in the dismantling of the main synchronous converter in order to repair the small booster.

Another way to construct such a machine is to make it a revolving field machine, mounting the field on an extension of the shaft beyond the bearing of the collector-ring end of the synchronous converter.

As the armature is stationary, the leads from the secondary of the transformer are led directly to this winding, and from this winding to the collector rings of the synchronous converter.

This arrangement has the twofold advantage of being accessible, and not interfering with the ventilation or accessibility of the synchronous converter. This booster can be applied to any standard converter and being overhung, it is possible to carry a spare machine which can be placed in position quickly and without interfering with the body of the main synchronous converter.

5. The next development is very radical and is unlike any of the other schemes used. It was first proposed by J. L. Woodbridge some time ago. It has been known for some time that the ratio of conversion between the alternating current and direct current sides of a synchronous converter could be changed by varying the width of the pole-face. The Woodbridge method makes use of this idea in a very simple and yet effective way.

Fig. 4 shows a two-pole synchronous converter equipped in accordance with this idea. Each field pole is divided into three sections on each side of which are two windings. One of the windings on each section is the main shunt winding, and the other is the regulating winding. All the main windings are connected in series and excited in the ordinary manner. The regulating windings, however, are connected differently. The windings on the two outer sections of all poles are connected in series with one another and the windings of all the central sections are connected in series with one another.

The voltage of the direct-current side of the converter is increased by exciting all the outer sections in a direction to assist the main shunt field, and the middle section an equal amount in opposition to the main field. This condition is shown in Fig. 5. If both these windings are excited in the opposite direction the direct voltage will be lowered. Fig. 6 shows this condition.

All that is needed in this arrangement is a field rheostat in the regulating field circuits in addition to the main field rheostat ordinarily used.

The first question that comes up with this scheme is what effect it has on the power-factor? A number of machines arranged this way have been designed and placed in operation. With these machines the power-factor can be held constant at all loads, yet all the range in voltage desired can be obtained.

6. Since this method was proposed, another and still simpler method has been brought out. This scheme was proposed by Mr. J. L. Burnham. Instead of making each pole with three sections and with two windings on each, only two sections are used. On each section only one winding is used. The large section corresponds to the main shunt winding on an ordinary synchronous converter, while the regulation is obtained entirely by changing the excitation of the smaller section, exciting it in one direction to boost the voltage, and in the other to lower the voltage.

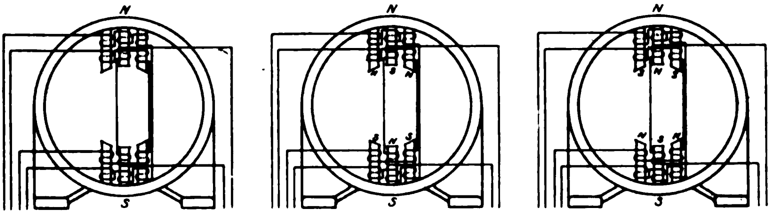

Fig 4 Fig 5 Fig 6

Figs. 4, 5, 6.

Anti-hunting devices of many types have been designed and put in operation, most of which have been reasonably successful. The latest, and in many ways the most efficient form of bridge, is formed by placing some copper rods directly through the face of the pole tips. These copper rods are all joined together by heavy copper rings, thus forming a complete squirrel-cage winding similar to that used on the rotor of an induction motor.

These rods being placed directly through the pole face are naturally in the main flux and consequently form very efficient dampers.

Nothing has been said as yet about transformer connections to be used with synchronous converters. There are many conditions existing in different parts of the country which have made it advisable to use some special form of connection for the transformers, but the general practice is to use the diametrical connection with all six-phase machines. This connection is particularly useful in lighting work, as it provides a ready means for obtaining a neutral. With three-phase converters the transformers are usually connected in delta.

A paper to be presented at the 225th meeting of the American Institute of Electrical Engineers, New York, February 14, 1908.

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SOME FEATURES OF RAILWAY CONVERTER DESIGN AND OPERATION

BY J. E. WOODBRIDGE

There are now in service in this country in railway work alone, synchronous converters with an aggregate capacity of nearly 1,000,000 kw. In spite of the wide use of this machine, some features of its design and operation are not generally clearly understood, or are quite generally misunderstood. It is the purpose of the following paper to take up three of these features as follows.

Six-phase versus three-phase converters. Of the above aggregate capacity, something like one-third consists of machines with six collector rings tapped into the armature winding at six points per pair of poles and termed six-phase converters, although the electromotive forces delivered to them are as truly three-phase as are those delivered to machines with three collector rings. Although it is generally known that the addition of three collector rings to a given three-phase converter reduces the armature $I^2 R$ losses considerably on unity power-factor, it has been heretofore assumed that wattless currents increase these losses of both types of converters by about the same quantity, but not in the same proportion, so that the gain of the six-phase machine is slight on low power-factors.

It has heretofore been shown mathematically, and noted in actual practice, that the armature conductors of a converter nearest the collector ring taps, run warmer than those midway between the collector ring taps. The distribution of the armature $I^2 R$ losses (assuming a winding of uniform cross-section, which is the invariable construction) is shown in the upper part of the accompanying diagram, Fig. 1, the two curves of which represent the theoretical $I^2 R$ loss of a six-ring machine run with the same load, in one case with six-phase, and in the other case with three-phase supply, both at unity power-factor. These curves assume theoretical voltage ratios which are closely approached in practice, but neglect the losses due to unconverted power such as unbalancing, core-loss, incipient hunting, harmonics set up by differences in wave-form, etc., These losses are small, and affect both curves by about the same amount. The vertical scale is given in terms of the heat developed in the same winding when generating the same power in direct current mechanically driven. It will be noted that in this case the operation of the machine as a three-phase converter as compared with its operation as a six-phase converter, increases the average $I^2 R$ loss slightly over 100 per cent. and increases the $I^2 R$ loss in the unfavorably situated bars adjacent to the collector rings almost 200 per cent. in addition to concentrating these more highly heated bars into three groups per pair of poles, instead of six groups, thus reducing the ability of the machine to equalize the temperatures by thermal conduction through the insulation and armature iron.

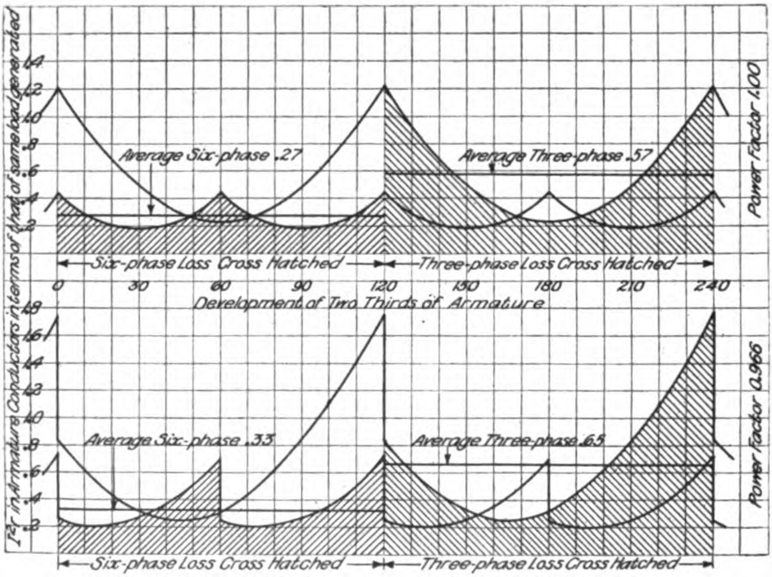

Fig. 1.

It has been generally assumed that this considerable advantage of the six-phase over the three-phase machine is reduced in case of lower power-factors. It can be shown mathematically (see appendix 1) that the distribution in case of a phase displacement of 15 degrees giving a power-factor of 96.6 per cent.; that is, a wattless current equal to about 28 per cent. of the energy current, is as indicated in the lower half of Fig. 1. In this case it will be noted that the average heating of the whole winding for the same load is in the case of the six-phase operation increased from 0.27 to 0.33 of the reference figure, which is the heat developed by the same direct current load mechanically derived. In the case of the three-phase operation, the average $I^2 R$ loss rises by a lesser proportion from 0.57 to 0.65, but the addition of the wattless current has also the peculiar effect of shifting the heat distribution from one side to the other of the collector ring tap, considerably reducing the heating of the bars to one side of the tap and greatly increasing that of the bars on the other side. A lagging component shifts the heating to one side of the taps, and a leading current to the other side. It will be noted that the bar to one side of the collector ring tap is heated in the case of the six-phase operation to the extent of 0.71 of the reference figure, or about twice the average and three and a half times the minimum, whereas the corresponding bar of the three-phase machine is heated to the extent of 1.75 times the reference figure, or three times the average and seven times the minimum, and two and a half times the maximum with the same machine worked six-phase. Not only is the heat rather more badly crowded into a few bars by a given phase displacement in the case of the three-phase than in the six-phase converter, but these bars are again concentrated in three groups per pair of poles, instead of being distributed in six. Lower power-factors increase this heating and further crowd it into a few bars.

Even if the maximum heating were the same for the two methods of operation, the addition of three collector rings might be warranted by the better distribution of six-phase operation, but with the maximum heat generation two and a half times as great (even with a good power-factor) with only three collector rings the argument is that much stronger.

Of course, a three-phase converter for a given output may by increasing its size be built with more armature copper than a six-phase converter of the same rating; but in any event the three-phase machine may be safely increased in rating some 40 or 50 per cent. with no increased losses, and with a correspondingly higher efficiency by the addition of three more collector rings and, if necessary, a corresponding extension of the commutator. This results in a corresponding reduction of core-loss for kilowatt capacity, which is a great aid to efficiency in railway work of low load-factor.

The arguments against the six-phase form of converter are three in number: first, the increased number of parts of the machine; secondly, the additional number of cables; thirdly, the alleged relative complication of the transformer circuits.

Unless extreme care is taken in the construction of a converter, to get the magnetic reluctance of all poles exactly the same, it is found that the commutation of any three-phase machine is improved by the addition of equalizing rings over and above those constituting the three collector rings. Six or more equalizing rings being advisable for this reason, the increased complication of the machine for six-phase operation is reduced to the addition of three collector rings, the necessary brush rigging and terminals. These additions are negligible in the case of large machines where each of three rings must be considerably broader than each of six in order to carry double the current, and where also the use of six rings allows the brush rigging to be divided into two equal parts, one each side of the shaft, where with three-phase converters two-thirds of the brush rigging must be on one side of the shaft. Further, the six narrow rings are better ventilated than three broad ones, and they run cooler.

In the matter of cables, the objection to six-phase machines applies only to small units where the whole current of one of the three phases can be carried in one cable. In machines of 500 kw. or more, even at railway voltage, it is convenient to use six alternating current cables, two in parallel on each phase, for the supply of a three-phase converter, and in larger machines it is necessary to do so. The six-phase machine has an alternating current input per ring practically equal to one-half the direct current output, so that wherever two cables or a multiple of two are used for one pole of the direct-current output, cables of the same size may be used for the alternating-current leads, the machine being as convenient in this respect as the three-phase converter.

In the matter of transformer connections, the so-called diametrical connection is almost invariably used, each transformer having one secondary winding, the ends of which are connected respectively to two collector rings, the connection being even simpler than that of three-phase converters, in that no "Y" or delta need be made. If reactive-coils or other devices are serially connected in the low-tension alternating-current circuits, these need be, and commonly are, only three phase; one phase being connected in series with each diameter of the converter, and so to speak, boosting or lowering the voltage of both ends of the diameter. (Fig. 2). This is a positive advantage for the six-phase equipment, in that the winding of the serially connected devices need carry only one-half of the current of the winding of a similar device for a three-phase converter. For the above reasons all converters of 500 kw. capacity and over, made by one manufacturing company in this country are built for six-phase operation.

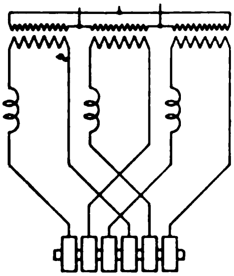

FIG. 2.

The alternating-current starting of synchronous converters. Some 50 per cent. of the above mentioned total of railway converters in service in this country, are equipped with switches and connections for starting the machines from rest by means of the direct application of alternating electromotive forces to their armature windings through the collector rings, these electromotive forces being a fraction of those subsequently switched on for operation. In spite of the extensive use and general success of this method of starting, advocates and users of other methods attribute great disadvantages to it. Following is a more complete statement of the case than has heretofore been set forth.

A line of 25-cycle converters with pole-arcs equal to 75 or 80 per cent. of the pole-pitch, with air-gaps of one-quarter to three-eighths of an inch, and with full load armature ampere-turns per pole approximately equal to the shunt field ampere-turns per pole (at rated voltage normal speed unity power-factor no load) and with short-circuiting squirrel-cage, anti-hunting winding embedded in the pole faces, will in general start from rest with some 20 to 25 per cent. of rated alternating voltage impressed across their collector-rings, and will take at this voltage at rest approximately twice full load current; that is, 40 to 50 per cent. of full-load volt-amperes, this current having a low power-factor, as the machine is acting under this condition as an induction motor with a variable and rather wide air-gap, the pole-face windings serving as a short-circuited secondary. When started in this way such a machine will run up to synchronism without increase of voltage, and may be locked in step by excitation of the field windings.

The air-gaps and other characteristics above mentioned, are those most desirable for operation in railway work, and have been chosen as giving best the conversion and commutation. The good qualities in alternating current starting which result from them are merely incidental. The high armature reaction relatively to that of generators is highly advisable in compound-wound converters. High armature reaction, resulting in field distortion in generators, which is disastrous to commutation, has no such effect in synchronous converters since the field distortion of the direct-current output is always balanced by the field distortion of the alternating-current input. Increase of armature reaction causes a reduction of the lagging or leading currents set up by a given percentage difference of the field strength from the proper value for unity power-factor. Machines of these characteristics will stand a most surprising departure from proper field excitation when the increased heating pointed out above is considered. This feature is advisable for machines left in the charge of suburban railway station agents or other unskilled engineers in out-of-the-way sub-stations. In extreme cases, machines of these characteristics will operate on the usual low load-factor of interurban service with no shunt-field excitation whatever, as has been proved in several cases by mistakes in connecting up the field windings, mistakes not discovered until after a considerable period of operation. Other things, including full-load efficiency, being the same, a machine of high armature reactance will have a lower core-loss than a machine of low armature reaction, and will show a higher all-day efficiency on a low load-factor such as that of railway work.

Advocates of converters with a lower armature reaction assert that machines with high armature reaction have low synchronizing power, whatever that term may mean. It is certain that machines with the characteristics above outlined, will follow without falling out of step the most violent fluctuations of speed that prime-movers can set up. One such 600-volt converter has been run with full-current output down to 50 volts. They will carry, when operating single-phase, a railway load of the usual fluctuating character of interurban service, without signs of distress. In the rough and ready service that railway converters often have to stand, it is certain that a machine with stiff fields and low armature reaction will kick out its automatic alternating current switch and go out of service more readily in case of an outside disturbance, such as a single-phase short-circuit on the alternating current lines, than will a machine with higher armature reaction. The machines outlined above do not drop out of step with direct current short-circuits when protected by the usual breakers, and the writer has never heard of a well authenticated case of one of these machines slipping a pole and continuing to run with direct-current polarity reversed, either from a direct current or an alternating current short-circuit, although this action has in one or two cases been suspected. In the matter of hunting, opinion is divided between the advisability of high or low armature reaction, but there are converters aggregating several tens of thousands of kw. capacity in service with high armature reaction even without the usual short-circuiting pole face windings.

It is interesting to compare the above minimum limit of alternating self-starting current with the minimum limit of current required for starting induction motor before passing to the more practical field of service conditions. The torque required to start a converter from rest after a few days' shut-down may be expressed as 12 to 15 per cent. of full-load torque, the latter term representing the torque which would set up by full-load current generated. In other words, when started as a direct-current motor, 12 to 15 per cent, of full-load current may be required, if the field strength is normal. The induction motor designed to start a six-pole converter must have four poles in order to bring the machine up to synchronism. Since an induction motor requires at least as great a current to develop a given torque at standstill as at full speed, the development of the above torque corresponds to 20 to 25 per cent. of converter full-load current input, or about one-half that required for self-starting from the alternating-current side. In other words, the advantage that the induction motor gains from design for one purpose only, is partly offset by its higher synchronous speed. With the same margin, the self-starting method should take in service about twice the volt-amperes of the other. In practice a large factor of safety in the form of a margin of voltage over that required must, of course, be allowed with either method, to cover low impressed voltage, extra friction, etc.

In actual service using this method, 25-cycle converters under 500 kw. in size, are usually started from mid-taps in the transformer windings, giving the converter one-half rated voltage, since it is expedient to locate a tap at the middle of the winding rather than at any other point more exactly suited to the purpose. Where reactive coils are used, these are connected in the starting circuit as shown in the accompanying diagram of connections, Fig. 3, since it is found that one-half voltage is sufficient to start such a converter through the usual 15 per cent. reactance. Early practice used a mid-tap in each of the three sides of the delta, but the change of phase when throwing from half to full voltage was found to give a greater swing, and the apparent unbalancing of the load with the connection shown was found to be negligible. The converter starting current under this condition, amounts to about one and three-quarters to twice full-load current, this being, by virtue of the compensator action of the half-voltage tap, equal to or less than full-load primary volt-amperes. A converter started in this way, runs up to synchronous speed in from 15 to 25 seconds with negligible sparking at the direct-current brushes.

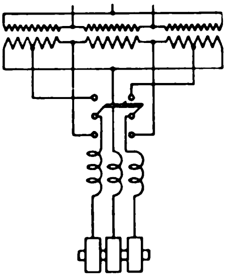

FIG. 3.

It may lock in step with either positive or negative polarity to line, wrong polarity being customarily taken care of by a field reversing-switch, which closes the field for self-excitation without field rheostat in circuit, with a reversed connection for building up the machine when rotating in the direction set up by the alternating currents. The current sent by the armature through the field winding, acts against the flux induced by the alternating magnetizing current, driving this flux out in the form of magnetic leakage beween the poles. Friction under this condition drags the armature back until the electromotive force delivered to the brushes just reverses, when the field again reverses and holds the armature from falling back any further. The field reversing switch may then be safely thrown over into the normal connection, when the machine will build up with proper polarity to line. This action at starting voltage, calls for a volt-ampere input less than one-half full-load watts. When other compound-wound machines are carrying load in a railway sub-station, the polarity may be instantly corrected by closing the switch or switches which parallel the series field of the newly started machine with those already in operation. The division of direct current between the several series fields, serves as separate excitation to slip a pole of the newly started converter at starting voltage. With correct polarity and field excited, the machine may be thrown instantly from half voltage to full voltage with a momentary volt-ampere input not exceeding three-quarters rated watts, this input settling down to usual no-load value as soon as the field has time to build up.

Twenty-five cycle converters of 500 kw. and over, when fitted for alternating-current starting, are commonly equipped with tandem switches designed to connect them first to taps which will deliver to the windings one-third normal voltage. With this low voltage the reactive coils are cut out, the volt-amperes expended in the reactive coil during starting being thus saved. Two steps are necessary to pass from one-third to full voltage, since one jump would give too great a swing of current. These are commonly made by two double-throw switches connected tandem, to prevent the possibility of short-circuits. The arrangement is shown with complete connections for a six-phase converter with a three-phase reactance in the accompanying diagram, Fig. 4. With this arrangement, 25-cycle converters commonly take about two-thirds to three-quarters of rated full load volt-amperes in starting, and get up to speed in 20 to 25 seconds. The advantages of this self-synchronizing method of starting in times of emergency, and at all times in small outlying sub-stations, are obvious.

In that the same power is used for starting as for running without auxiliary apparatus other than switches, no reserve or duplicate method of starting is required, there being no more need of such a duplicate than (for example) for the starting of a steam engine. This results in simplifying the equipment and operation. When starting is accomplished by means of an induction motor, means of starting from the direct-current side are warranted by the helplessness of the converter in case the motor fails. The induction motor secondary has necessarily a high resistance in order to give good torque at standstill, and this resistance is usually made internal. As the motor is only intended to run for a short time starting cold, its design is cut fine, giving high densities. In cases of trouble giving several shutdowns in quick succession, it may become impossible to start the converters without waiting for their induction motors to cool down. Instances of this kind have occurred. Self-starting converters may be run up repeatedly as quickly as they will slow down for an indefinite period without overheating.

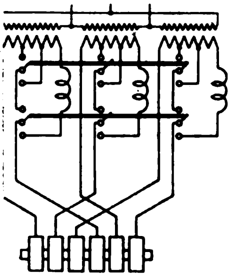

FIG. 4.

A six-phase machine will start with two diameters and will operate with reduced capacity on two diameters, just as a three-phase machine will operate on open delta. Incidentally, this is a slight advantage of the six-phase machine over the three-phase, in that when a transformer fails, it can be readily cut out of service in the case of a six-phase machine, whereas, in two cases out of three, with a three-phase machine, it is necessary to make several cable alterations to preserve the alternating current starting features.

When starting with alternating currents directly applied, it is advisable to open the field circuits, as if these are left closed, considerably greater currents are required, and the starting torque is reduced. The shunt field circuits should be opened at several places, otherwise the induced voltage may be too high. The shunt-field reversing switch above mentioned, and field break-up switch being combined, no other means of opening the field should be provided, so that if this switch is left closed, the shunt field will be short-circuited through the armature, and no high voltage can result. The equalizing connections of the series field must of course, be opened during starting, and the shunt for the series field is also provided with a switch to be opened at this time to cut down the draught of current. This shunt, as customarily supplied, following the established precedent of the days of engine-driven generators, seems with its switch to be a rather useless appendage, since it is rarely, if ever,

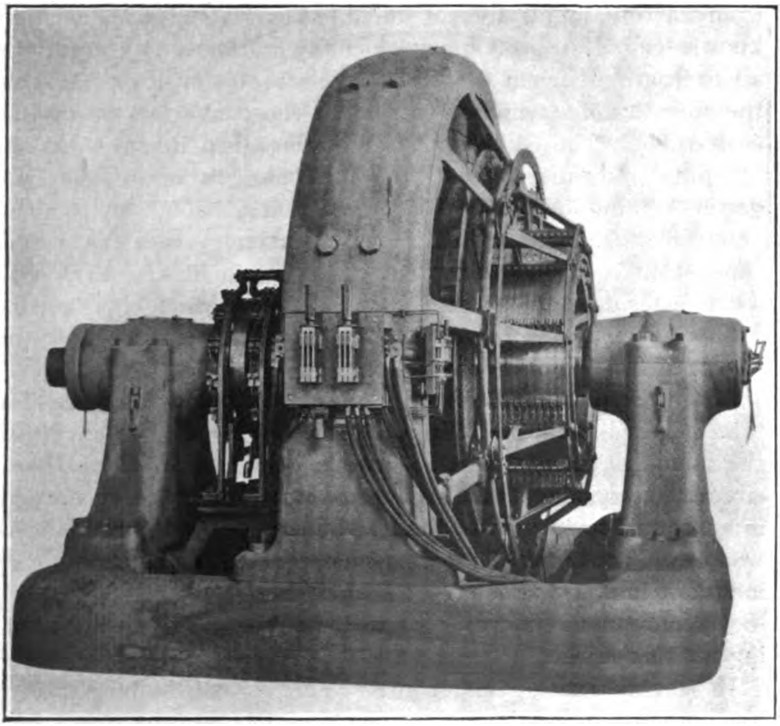

Fig. 5.

used to adjust the compounding; and it is useless for adjusting the division of load fluctuations, in that its usefulness for this purpose depends altogether on bad equalizing, which does not usually exist in compact sub-stations.

When a number of converters on one system are started simultaneously, as after a shutdown, the starting currents are sufficient to lower the voltage considerably, especially if but one generator is in service. The lowering of voltage at this time is, of course, immaterial, unless sufficient to prevent the converters from starting, no instance of which has ever come to the writer's knowledge. It is customary on many railroads to connect up all alternating-current feeders at once after a shutdown, allowing the sub-station attendants to run up the converters as rapidly as possible. The lack of perfect synchronism between the attendants' movements and the rapid acceleration of the converters coming up to speed in a few seconds, is sufficient to avoid an overdraught of current, even in extreme cases. At other times, that is, when the system is carrying load, the starting of a converter does not cause any disturbance which it is possible to distinguish on any part of the system, from those set up by the ordinary fluctuations of railway load.

A synchronous converter is a better self-starting machine than is a constant-speed induction motor of high efficiency and the same frequency, size, and speed. Such a motor with short-circuited secondary, takes in a service for starting a volt-ampere input equal to an overload of 25 to 50 per cent. Some engineers who would not hesitate to arrange for the self-starting of such an induction motor, do not favor the self-starting of the corresponding synchronous converter, so great has been the misunderstanding of this subject.

In several cities of this country converters of the largest sizes are regularly started from the alternating current side, their supply of power coming from lighting systems supplying lights through other converters from the same alternating current network. In one city, converters of 1000 and 1500 kw. capacity are supplied from a system carrying a lighting load, and although these converters are equipped with induction motors for starting purposes, the starting is usually accomplished by the above described self-starting means.

Compounding of converters Although it is generally known that converters cannot be compounded without reactance in the circuit, and that the smaller the reactance the greater must be the strength of the series field for the same regulation, few engineers have any idea of the best values of reactance and series field strength, or the shape of the compounding curve with different values of resistance and reactance; or, what is more important, the best transformer ratio and best setting of shunt field rheostats.

Before taking up the rather complex reactions with both resistance and reactance in circuit, a mental picture of the effect of reactance alone, in the simplest case, can be obtained from the vector diagram Fig. 6, where the large triangle represents a three-phase voltage, as delivered to a three-phase reactance and through this to a converter, the voltage of which is shown as a circle. At no load, and neglecting losses, assuming a shunt-field excitation for unity power factor; that is, no leading or lagging current,

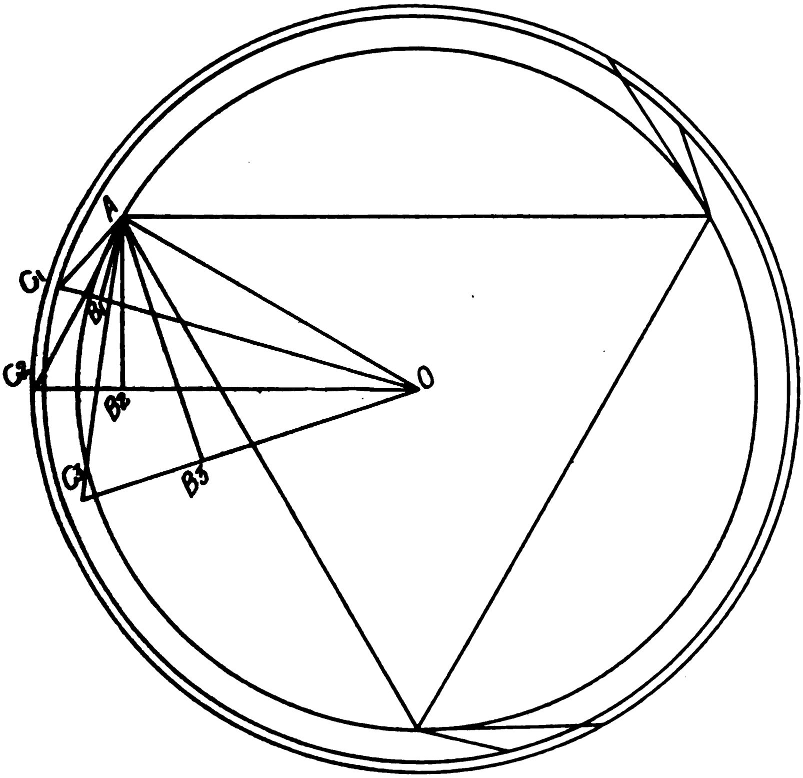

Fig. 6.

there is no drop in the reactance owing to the absence of any current, and the impressed voltage is delivered without change, the inside circle representing the converter voltage under this condition. At full load the energy current flowing through the reactance gives a reactive drop at right angles with the electromotive force, delivered to the converter, which for one phase may be represented by the line $A\ B_1$. The impressed voltage of one phase may be represented by the line $O\ A$, the voltage delivered to the converter (if the converter is shunt wound) by the line $O\ B_1$, with which $A\ B_1$, the reactance drop, makes a right angle, since the current is assumed to be in phase with the converter or delivered electromotive force, and the reactance drop is normal to the current. If now the converter is compound wound, the leading current drawn by the increased field strength at full load gives a reactive drop B_1C_1 which increases the delivered electromotive force from the value $O\ B_1$ to $O\ C_1$, the reactive drop (which is really a rise) of the resultant current being $A\ C_1$. The middle circle drawn through the point C_1 and corresponding points of the other phases then represents the converter electromotive force at full load, the collector ring represented by the point C_1 lagging behind the impressed electromotive force by the angle $A\ O\ C_1$ and being pushed out (so to speak) by the reactive drop of the leading current from B_1 to C_1.

With greater reactance, the lines $A\ B_1$ and B_1C_1 both become longer, always retaining the same proportion, since one is caused by the energy current and the other by the magnetizing or leading current, both of which are unaffected by the reactance in circuit, neglecting variation of shunt field. Thus with twice the reactance, the resultant reactive drop increases to $A\ C_2$ and with three times the reactance to $A\ C_3$, the triangles $A\ B_2\ C_2$ and $A\ B_3C_3$ being exactly similar to $A\ B_1C_1$.

It may be seen that increasing reactance enlarges the delivered voltage up to a certain limit, after which it diminishes, since the increasing drop of the energy current $A\ B_3$ diminishes the other side $O\ B_3$ of the right angle triangle $O\ A\ B_3$ with fixed hypothenuse $O\ A$ so rapidly that the effect of the compounding B_3C_3 can not increase rapidly enough to make up for it.

With greater series field strength and fixed reactance the component B_1C_1 increases at the expense of reduced power factor, $A\ B_1$ remaining constant. Since the resultant drop $A\ C_1$ is at right angles with the current it may readily be seen that the more this drop departs from a right angle with the delivered electromotive force $O\ C_1$ the worse the power-factor becomes.

If we assume that with changing load the leading current increases in direct ratio with the energy current giving a constant power-factor and constant angle between the reactive drop and the delivered electromotive force, the effect of overloads becomes in this simple case the same as that of increased reactance, an overload of 100 per cent. with the initial reactance doubling the reactive drop of the energy current from the full load value $A\ B_1$ to $A\ B_2$ and that of the leading current from $B_1\ C_1$ to $B_2 C_2$ giving again a resultant drop of AC_2. In general, with any value of reactance and series field, the compounding curve is not straight, but droops on the higher loads. This can be shown by reference to the same figure, taking an extreme overload to make the drop obvious. Three times full-load current gives a reactive drop $A\ C_3$ and a delivered electromotive force $O\ C_3$ which is less than the full load or 100 per cent overload values $O\ C_1$ and $O\ C_2$ owing again to the shortening of $O\ B_3$ as $A\ B_3$ lengthens. For the same reason it will be noted that the rise of voltage from no load to full load is greater than that from full load to 100 per cent. overload. In practice, other things, such as magnetic leakage and weakening shunt field, increase the droop. It may be mentioned that $O\ A\ C_1$ represents fairly well ordinary service conditions at full load, the effect of resistance ~~being to bring~~ C_1 back to the inside circle. The saturation of reactances cuts down the overload triangles to smaller figures than here shown.

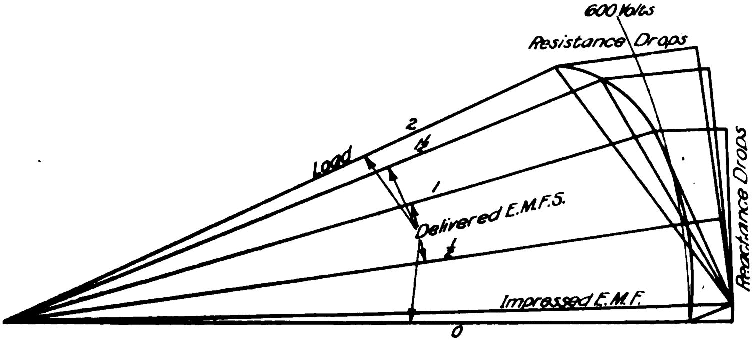

FIG. 7.

Over-compounding has gone out of fashion, partly thanks to the low power-factors accompanying over-compounding with converters supplied from a system with considerable alternating current drop, and partly due to the connection of converter sub-stations directly to trolley lines, without feeder drop at their nearest points, both of which factors have led to a more rational consideration of direct current feeder drop. It is now considered advisable to have the maximum voltage applied to the car equipments when near the sub-stations fixed, and not dependent on over-compounding caused by their own or other loads.

In accordance with the established custom of assuming a drop of 10 per cent. at full load, which custom has prevailed in all constant potential work since the earliest days of the incandescent lamp, converter equipments are commonly assumed to be called upon to give flat compounding at the direct-current side with a total resistance in the alternating current circuits of 10 per cent., including transformer and converter resistance, constant potential being assumed back of this 10 per cent. resistance, usually at the power house.

To reduce the average heating, compound converters should have their shunt fields so adjusted as to draw a considerable lagging current at no load. This does not materially change the compounding. For best operation under fluctuations from no load to 100 per cent. overload, the best shunt field setting would be such as to give unity power-factor at some point well above average load such as about full rated load. This would give about one-half to three-quarters full-load current lagging at no load, according to the series field strength of the converters, which is impracticable in service, as substation attendants would not operate in this way, but would increase the direct current voltage. A more practical assumption is unity power-factor at one-half rated load, that is the same amount of lagging current at no load as leading current at full load. It can be shown mathematically (see appendix 2) that for flat compounding between no load and full load, with unity power-factor midway minimum wattless current at no load and full load, *i.e.* best power-factors, are obtained with a reactance equal to the resistance multiplied by the square root of one plus two divided by the percentage resistance drop. With 10 per cent. resistance this calls for 46 per cent. reactance, and a wattless current at no load and full load equal two 23 per cent. of full-load energy current.

This compares with existing established practice as follows: A large number of railway converters in this country are equipped with series fields of such strength (when shunted) as to balance one-half full-load armature ampere-turns at full load. In other words, such a converter with shunt field rheostat set for unity power-factor at zero load, will (over and above energy current) draw a leading current at full load equal to one-half full-load current. In line with the above argument it will be assumed that these converters have their rheostats so set as to draw a lagging input equal to one-fourth full load current at no load, which will give unity power-factor at approximately one-half load, and a leading component equal to one-fourth full-load current at full load.

Many of these converters are equipped with 15 per cent. reactive coils; that is, reactive coils which, with full-load current, will show across the terminals of the winding in each phase 15 per cent. of the voltage of the circuit in which they are connected. Assuming about 5 per cent. reactance in the converter (high armature reaction) 3 to 3.5 per cent. in the transformers, and 1.5 to 2 per cent. in line and cables, the total reactance in circuit to the direct current brushes amounts to 25 per cent. This represents about the maximum reactance in commercial use in this country. It will also be assumed that constant potential is delivered to this circuit with a total resistance drop including that of transformers and converter to the direct current brushes of 10 per cent. at full load.

Assuming 600 volts as the no-load pressure, the compounding for both the best value of reactance and this representative case is given in the following table, the figures being calculated by the method of complex quantities, due allowance being made for magnetic leakage and saturation of reactances from test records, also for variation of shunt fields with voltage.

All power-factors below one-half load represent lagging current, while those above represent leading current.

The power factors *at the converter* are also given for the various loads, these being independent of the reactance in circuit, and dependent only on the relation of the wattless and energy inputs drawn respectively by the field excitation and the load. While the power-factor *of the input* of the 46 per cent. reactance case varies with the load, that of the input to the 25 per cent. reactance and 50% series field combination is above 99% from one-half load to one-hundred per cent overload, the leading effect of the

POWER-FACTORS AT CONVERTERS AND DIRECT CURRENT VOLTS.

10% resistance			Unity power-factor at halfload			
	46% reactance 46% series field		25% reactance 50% series field		12½% reactance 80% series field	
Load	Volts	Power factor %	Volts	Power factor %	Volts	Power factor %
0	600	19	600	16	600	10
0.25	614	93	605	90	601	82
0.5	619	100	605	100	599	100
0.75	615	99	602	99	597	97
1.00	600	98	596	97	593	93
1.5	540	97	567	95	576	89
2.0	475	97	533	94	550	88

series field almost exactly balancing the lagging effect of the reactance between these limits.

The drop in pressure of the theoretical case on overloads puts it out of consideration for practical service, but that of the 25 per cent. reactance case is, in the writer's opinion not objectionable, as it enables a converter to shirk its work rather than trip its breaker when overloaded, and tends in a properly designed network to throw excessive overloads to neighboring sub-stations. It also eases the blow of a short-circuit.

When separate reactive-coils are not used, dependence being placed on the internal reactance of converter, transformers and line, the total reactance of the circuit may be assumed to be as low as one-half that given above, or about 12.5 per cent., especially where converters of low armature reaction and consequently of low internal reactance are used. This represents about the minimum reactance in commercial use. To get the same regulation between no load and full load with this smaller reactance, the series field of the converter must balance an armature reaction of over 80 per cent. instead of 50 per cent; that is, a leading component equal to more than 80 per cent. of full load current must flow in the armature to balance the effect of the series field at full load. Assuming again that the shunt field is so adjusted as to give unity power-factor at half load; that is, 40 per cent. of full-load current lagging at no load, the table gives the power-factors for this case at various loads. It will be noted that while the 25 per cent. reactance gives much better regulation and only slightly lower power-factors than the best theoretical reactance, the 12.5 per cent. reactance gives much lower power-factors, the effects of which can be imagined from the heat distribution curves given in the first part of this paper.

It will be noted also that the small reactance and more powerful series field give a somewhat better regulation on heavy overloads, but it is doubtful whether this regulation can be actually reached, as it calls for heavy leading currents which it is difficult to obtain even with a machine of low armature reaction; for example, at twice full load, over full-load leading current is required. Under this condition the armature reaction is opposed to the field flux, tending to cause magnetic leakage. In this case the power-factor of the system varies with the load, as the series field greatly outweighs the influence of the reactance.

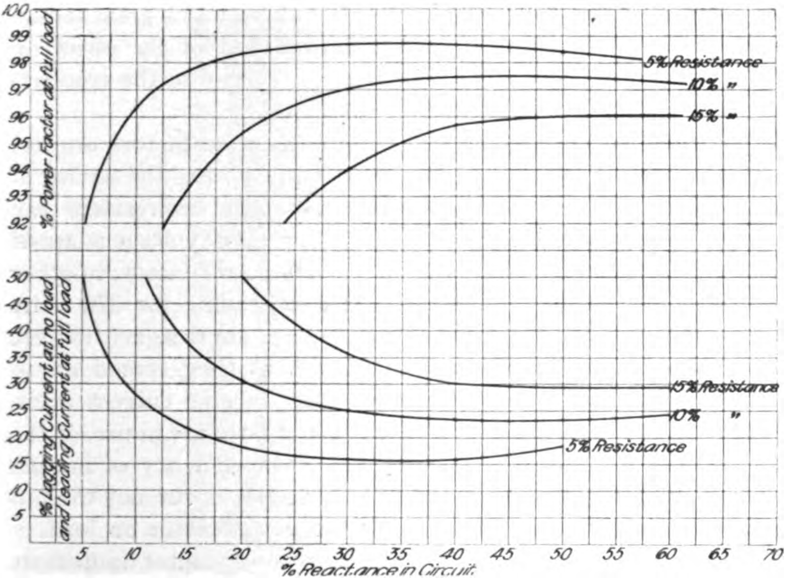

FIG. 8.

The above discussion disregards the reactance and resistance of the generators on the score that the fluctuations of load on one sub-station will not disturb the main station voltage of a large system, and will be compensated by hand adjustments of the field rheostats on a moderate size system and by automatic means on a small system, so that constant potential at the mai station bus-bars may be assumed.

Records of compounding tests under similar conditions check these results as closely as might be expected, consistent results from tests under service conditions being unobtainable owing to fluctuations of other loads, voltage, etc.

Such a high reactance as the maximum above calculated might give instability, but no such case has ever been noticed with 25 per cent. reactance, even with high resistance drops and converters of high armature reaction without pole-face windings. In one case of extreme hunting due to excessive line drop, the writer inserted in circuit a reactance of 20 per cent., the result being a slight increase of the angle of oscillation of the armatures as noted by a stroboscopic method; but there was a great reduction of the periodicity of the oscillation, and of the effect on the voltage, due to the variable input of energy to the converters and consequent variation of line drop.

In actual practice such good results in power-factors are not obtained owing to lack of instructions concerning the setting of field rheostats. Transformers for compound converters are almost invariably designed to give a secondary voltage adapted to the ratio of conversion of no-load unity power-factor; in other words, if the ratio of conversion is 0.62, calling for 370 volts to give 600 direct voltage, the transformers are designed to give 370 volts instead of 390 volts or more, as they should do to deliver normal direct voltage with proper lagging current at no load. Even where transformers of proper ratio are in use, or the alternating voltage is sufficiently high, the tendency of human nature to push up the direct voltage tends to cut out the no-load lagging component and lower the power-factor on load.

This is particularly the case where power-factor indicators are installed in the circuits of the converters. Even where these instruments are properly connected, which frequently is not the case, the natural tendency of the attendants is to bring up the excitation on starting a converter until the power-factor indicator shows approximately unity power-factor. These instruments are frequently so connected as to show the power-factor at a point with considerable reactance between it and the converter. In this case their readings are absolutely misleading, an indicated power-factor of 97 per cent. leading (for example) often meaning a power-factor at the converter of 90 per cent. or less. While it may be possible to get attendants to set their rheostats for proper voltage, if this does not call for more than 25 per cent. of full-load current at no load, which does not make much of a showing on an alternating current ammeter capable of reading twice full load, 40 per cent. is much more difficult.

In city work with comparatively small fluctuations, converters of the above series field characteristics, have been installed, but without series reactive coils, the argument being that these are unnecessary on comparatively steady loads. It would be much more satisfactory to omit the series winding and install the reactance, in order to give the attendants an opportunity to adjust their voltage by hand with smaller wattless currents.

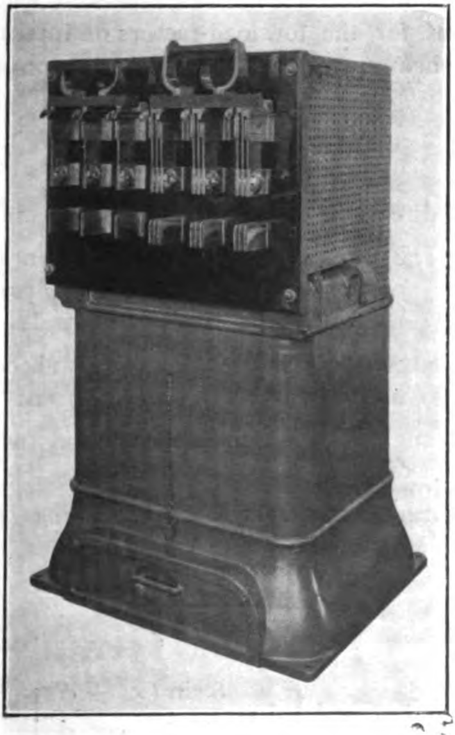

Fig. 9.

In general, the writer contends that best practice, with systems approximating 10 per cent. resistance, is the increase of the natural reactance of the circuits to approximately 25 per cent., and the use of a series field of such strength as to balance about one-half full-load armature ampere-turns, with transformer ratios such as to give normal direct voltage with about one-quarter full-load current lagging at no load; converter field rheostats to be set for normal direct voltage regardless of power-factor, and main station voltage to be kept constant at such a figure as will give unity power-factor at and above such a load as gives an average of one-half load or more to the converters.

The result of existing practice is low power-factors on heavy loads, particularly with converters of low armature reaction, and more particularly in circuits of small reactance, which would probably give trouble in many cases, especially with three-phase converters, but for the low load-factors of interurban railway work and the heavy overloads for which the converters are designed.

APPENDIX I.

If I = direct current per path in armature of converter

and α = angle in electrical degrees between middle of one section (between collector taps) and plane of commutation, assumed neutral

and ϕ = angle of lag between current and counter electromotive force, alternating current

and β = angle between middle of section and any bar of of resistance, *r*.

Then alternating current per path in winding of three-phase

machine $= I \dfrac{8 \sin(\alpha + \phi)}{3\sqrt{3} \cos\phi}$

Resultant current $= I \left[1 = \dfrac{8 \sin(\alpha + \phi)}{3\sqrt{3} \cos\phi}\right]$

Heating of bar $= I_r^2 \left[1 - \dfrac{8 \sin(\overline{\alpha} + \phi}{3\sqrt{3} \cos\phi}\right]^2$

Ratio of heating to that of same load mechanically generated $= \left[1 - \dfrac{8 \sin(\alpha + \phi)}{3\sqrt{3} \cos\phi}\right]^2$

$$\text{Average ratio} = \frac{1}{\pi}\int_{\beta}^{\pi+\beta}\left[1 - \frac{8\sin(\alpha+\phi)}{3\sqrt{3}\cos\phi}\right]^2 d\alpha$$

$$= \frac{59}{27} - \frac{32\cos\beta}{3\pi\sqrt{3}} + \frac{32}{27}\tan^2\phi + \frac{32\tan\phi\sin\beta}{3\pi\sqrt{3}}$$

similarly the alternating current per path in winding of six-phase machine $= \frac{4\sin(\alpha+\phi)}{3\cos\phi}$

$$\text{Average ratio} = \frac{1}{\pi}\int_{\beta}^{\pi+\beta}\left[1 - \frac{4\sin(\alpha+\phi)}{3\cos\phi}\right] d\alpha$$

$$= \frac{17}{9} - \frac{16}{3\pi}\cos\beta + \frac{8}{9}\tan^2\beta + \frac{16}{3\pi}\tan\phi\sin\beta$$

These two expressions are plotted in Fig. 1.

β being O in the upper curves and 15° in the lower.

Average heating of whole winding of three-phase machine

$$= \frac{2\pi}{3}\int_{-\frac{\pi}{3}}^{\frac{\pi}{3}}\left[\frac{59}{27} - \frac{32\cos\beta}{3\pi\sqrt{3}} + \frac{32}{27}\tan^2\phi + \frac{32}{3\pi\sqrt{3}}\tan\phi\sin\beta\right] d\beta$$

$$= \frac{59}{27} - \frac{16}{\pi^2} + \frac{32}{27}\tan^2\phi$$

Similarly the loss in the six-phase winding integrated between $\beta = \frac{\pi}{6}$ and $\beta = -\frac{\pi}{6}$ gives average

$$= \frac{17}{9} - \frac{16}{\pi^2} + \frac{8}{9}\tan^2\phi$$

APPENDIX II.

If E = impressed electromotive force

and e_0 = delivered electromotive force at no load

and e_1 = delivered electromotive force at full load

and i_0 = lagging current at no load

and i_1 = energy current at full load

and r, $x j$ have their usual values.

Then leading current at full load = $-i_0$ since the wattless current is assumed same at zero as at full load.

At no load $E = e_0 + i_0 x + j i_0 r$

At full load $E = e_1 + i_1 r - i_0 x + j(i_0 r + i_1 x)$

Expanding these two quantities to get absolute values (when $c_0 = e_1$ since the delivered voltage is assumed to be the same at full load as at no load) gives

$$i_0 = \frac{i_1 r}{2 x} + \frac{i_1^2 r^2}{4 e_0 x} + \frac{i_1^2 x}{4 e_0}$$

Differentiating this expression with respect to x to obtain the value of x which give the lowest value of i_0 gives

$$\frac{d i_0}{d x} = \frac{-i_1 r}{2 x 2} - \frac{i_1^2 r^2}{4 e_0 x^2} + \frac{i_1^2}{4 e_0} = 0$$

$$X = r \sqrt{\frac{2 c_0}{i_1 r} + 1}.$$

This expression is plotted in Fig. 8.

DISCUSSION ON "COMPARATIVE PERFORMANCE OF STEAM AND ELECTRIC LOCOMOTIVES", AT NEW YORK, NOVEMBER 8, 1907.

(*Subject to final revision for the Transactions.*)

William J. Wilgus: Instead of apologizing for adding to the number of papers on the electrification of steam railroads, the author should feel entitled to congratulations for calling attention to many of the advantages of the electric locomotive that have heretofore escaped analysis. In my judgment the cause is injured rather than benefited by arguments for the wholesale application of electricity to steam railroads, and it is pleasing to note the increasing tendency in our technical societies to sane discussions that will really enlighten the railroad officer anxious to be in the van of progress.

Unquestionably, electricity in heavy traction work has come to stay. As the author states, until now the reasons that have lead to the principal changes of motive power are entirely apart from questions of economy in operation. Conservative advocates of heavy electric traction, while urging its self-evident advantages in the abolition of the products of combustion in tunnels and cities, the increasing of terminal capacities, and opportunities for growth of traffic, have refrained from dwelling too strongly on saving money. They have been contented with the belief that more money could be made. The burden of additional interest charges, taxes, maintenance and depreciation attendant upon the substitution of electricity for the old form of motive power has very properly caused the careful engineer to pause in admitting even to himself that in addition to increased capacity to handle traffic, there might be a net saving in cost of operation. This cautiousness has sprung from the absence, until recently, of any actual data on the cost of heavy electric traction operation.

The pioneer electrical installation in heavy trunk-line service, on the New York Central & Hudson River Railroad, has now been in complete and successful operation since July 1, 1907, the gradual change from steam power having commenced in December, 1906. The working side by side of both kinds of motive power has given unsurpassed opportunities for the observation of their comparative capacity and efficiency. The results are even more gratifying than were expected; and substantiate many of the author's claims of superior capacity of electric equipment, although the conditions differ widely from those that he has assumed.

At this point it may be well to venture a word of caution on the subject of costs. Comparisons are worthless unless all elements of expense that will effect the results, are included. For instance, the cost of current delivered at the contact shoes should include not only costs of operation and maintenance, interest, depreciation, taxes and insurance on the power station, but likewise on the entire distributing system. If this is properly done, the real cost of current, as finally delivered at the electric equipment, will be found very largely to exceed the usual assumptions. The author's cost of current seems to me to be considerably too low.

On the other hand, the cost of maintenance and care of equipment should embrace not only wages and supplies, but also interest, taxes, insurance, maintenance and depreciation on the structures and real estate required to house and repair the equipment. Steam locomotives require extensive engine-houses, coal and water stations, ash-pits and appurtenances, often on very expensive lands, whereas electric equipment needs the simplest form of inspection sheds occupying limited areas of land. Also steam locomotives require extensive and complicated heavy-repair shops, usually at far distant points, that necessitate costly dead mileage and lengthy idle periods, while electric equipment because of its simplicity can be much more quickly repaired in nearby shops and returned to service. Many of these features have been mentioned by the author, but possibly their importance can be emphasized by giving some concrete examples from actual practice on the New York Central.

Because of less cost of maintenance of electrical equipment, and less idle time in shops, the greater cost of interest charges and depreciation is not only neutralized, but a net saving in repairs and fixed charges over steam equipment is effected of 19 per cent.

Electric locomotive inspection and light repairs, as compared with coaling, watering, drawing fires, repairs, etc., of steam locomotives shows a saving in time in favor of the former of over 4 hours per day, equal to 18 per cent.

The electric locomotive, while busy, is a much more nimble and efficient machine than the steam locomotive, showing an increase in daily ton-mileage of 25 per cent.

While not so important in freight service, the question of locomotive weight is a large factor in a comparison of the relative economy of handling passenger traffic by steam and electricity. For instance, in switching service at the Grand Central terminal, 65 per cent. of the total steam ton-mileage is due to locomotive or " dead " weight, while the electric locomotive percentage is but 54 per cent., a saving for the latter of 11 per cent.

In the regular schedule service, the steam locomotive shows 51 per cent. dead ton-mileage as against 35 per cent, for the electric equipment, a saving for the latter of 16 per cent. When we realize that this saving of " dead " ton-mileage has a direct proportionate effect on the cost of fuel and current, and an indirect effect on wages and fixed charges, its importance is manifest.

The author calls attention to the speed advantage of electric over steam locomotives in mountain-grade operation. This is strikingly apparent in the New York Central installation, where the increase in coal consumption for car ton-mileage in high-speed service as compared with slow-speed service, is shown to be 165 per cent., whereas under exactly the same conditions the increased consumption of current for electrical equipment is but 18 per cent., a difference in favor of electrical operation of 147 per cent.

The net result of all of the economical advantages of electric operation, over steam, *for the conditions existing on the New York Central*, after including all elements of cost of additional plant, shows a saving in summer months of from 12 per cent. to 27 per cent., depending on the character of service. A larger saving may be expected under winter conditions.

In addition to this saving, the nuisances and dangers from smoke and gas in the Park Avenue tunnel have been eliminated, and the capacity of the Grand Central terminal has been increased about one-third. Later when the New Haven Company effects its change of power, complete electrical operation in the tunnel will permit the use of shorter blocks, and correspondingly increase the capacity of the four-track main-line entrance to the terminal.

I feel sure that the author will be pleased to know of this actual demonstration of the correctness of many of his views, and that the members of the Institute, regardless of their advocacy of rival systems of electrification, will take pride in the successful inauguration of this pioneer trunk-line installation, on such a large and complicated scale.

It might be well to add to the authors' keynote *capacity*, the equally important one of *efficiency*, as the two combined, applied to the problem under consideration, will demonstrate whether or not the adoption of electricity is justifiable from the standpoint of economics.

Cary T. Hutchinson: I think that Mr. Armstrong gives the clearest statement of the capacity of steam and electric locomotives that I have seen. I agree with Mr. Armstrong that no project of electrification of trunk lines has up to the present been undertaken from an economical point of view. The matter has so far been determined by special considerations, such as the terminal problem in New York City, or the mountain-grade problem, or something similar. I doubt whether there ars sufficient data on hand to permit the making of an accurate estimate of the total annual cost of electrical operation of any steam road; all data on the subject that I have seen are subject to criticism from one point of view or another.

Mr. Armstrong considers especially two points; the relative capacity of steam and electric locomotives as machines, and the relative cost of operating the two. I think, however, that he does not emphasize strongly enough one feature of the capacity of electric locomotives, that is the capacity in *continuous service*.

Regardless of the type of motive power, the design of a locomotive is limited to a certain weight on each driving axle, the maximum being about 50,000 pounds; the coefficient of adhesion, as Mr. Armstrong states, in steam locomotive practice is taken at about 22 per cent. Each driving axle will then be able to deliver a tractive effort of 11,000 pounds, and a draw-bar-pull of, say, 9,000 pounds. A steam locomotive can exert this draw-bar pull continuously, up to a certain speed determined by the capacity of its boiler, which for the sake of illustration may be taken at eight miles per hour, so that in freight service each driving axle will give a continuous duty of 9,000 pounds. Owing to the limitations of space, no electric locomotive can be built to deliver continuously a draw-bar pull of 9,000 pounds per driving axle; probably 5,000 pounds is the maximum that can be obtained; that is to say, an electric locomotive cannot work *continuously* at a coefficient of adhesion greater than about 12 per cent. Therefore, for continuous service at low speeds a steam locomotive, for the same weight on drivers, can pull from 60 to 100 per cent. greater load than an electric locomotive.

The electric locomotive can, however, deliver this draw-bar pull at any speed that it is practicable to use, the limitation being fixed by the equipment and the track, and not by the locomotive. The draw-bar pull of the steam locomotive falls off from the critical speed of, say, eight miles per hour, as is well brought out by Mr. Armstrong in the paper, whereas an electric locomotive, designed for the purpose, will give its continuous drawbar pull at any practicable speed; hence, at a certain higher speed the two locomotives will pull equal loads continuously, at say about 16 miles per hour. At all higher speeds the electric locomotive will have the advantage.

The size of an electric motor is determined principally by the torque that it must exert and not by the speed at which it must exert this torque; hence a locomotive designed for 10 miles per hour and a draw-bar pull of say 5,000 pounds per axle, can, by changes in the windings, which will not change the size or weight of the motors, exert a draw-bar pull of 5,000 pounds at 40 miles per hour, or any other practicable speed. This is the great advantage of electric as compared with steam locomotives.

Another way of looking at the matter is that electric locomotives are designed for the *average* work to be done; steam locomotives for the *maximum* work since an electric locomotive designed for the average work will under all conditions easily be able to handle the maximum work. The use of the electric locomotive then makes it unnecessary to consider the ruling grade as a limiting feature to the capacity of the locomotive, whereas it must always be the limiting feature to the capacity of a steam locomotive. An illustration may make this clearer.

The six-axle Mallet compound locomotive used by one of the railways will pull, on the mountain division, having a grade of 2.2 per cent., an average of about 800 tons at a speed of 8.5 miles per hour, delivering therefore about 1,200 horse power at the driving wheel. The locomotive weighs 250 tons with tender; the output is equal to 4.8 horse power per ton total weight. An electric locomotive weighing 100 tons, all on the drivers, will haul the same load up the same grade at 15 miles per hour and will develop approximately 1,800 horse power, equal to 18 horse power per ton. In other words, the power developed per ton on drivers in the electric locomotive is four times as great as in the steam locomotive.

Moreover, an electric locomotive could easily be designed to exert the same draw-bar pull at a speed of 20 to 25 miles per hour, and have no greater weight, than for 15 miles per hour. This Mallet locomotive will pull a load of only 530 tons up the grade at a speed of 15 miles per hour, using Mr. Armstrong's curves as a basis. The comparison on a basis of 15 miles per hour is then:

MALLET.	
Engine and tender	250 tons
Train	330 tons
Total	580 tons
ELECTRIC	
Engine	100 tons
Train	800 tons
Total	900 tons

or the useful load at this speed is 2.4 times as great. This is merely another way of saying that steam service is incapable of handling heavy loads at high speeds.

The great advantage of the electric locomotive is, therefore, in the much higher speed possible. There is no inherent reason why a freight train should run at a lower speed than a passenger train; they do run at lower speeds simply because locomotives can not be built to haul them at the higher speeds, but the electric locomotive will probably change this and the speed of the freight service will be increased very greatly.

Another point should be noted in the above comparison. The steam locomotive weighs 150 tons more than the electric locomotive; assuming a duty of 100 miles per day, there are 15,000 ton-miles daily dead haul, which at the rate of 2 mills per ton mile amounts to about $30 per day, or say $10,000 per year. This is a clear saving in favor of electric locomotives. It can also be viewed as permitting an increase of 150 tons in the possible train load, and from this point of view the net earnings of an electric locomotive would be greater than that of a steam locomotive by the 150 tons extra load.

Something has been said by Mr. Armstrong about three-phase locomotives. I have recently decided to use the three-phase locomotives for the Cascade Mountain grade of the Great

Northern Railway, and among the reasons leading to this decision was the fact that the locomotive would have a fixed speed and could not be operated at a greater speed on the down grade. This equipment is for the freight service of the road only, at a place where much trouble has been caused by trains running away on the down grades.

Another reason leading to this decision was the recuperation on the down grade; this is valuable, not so much in the saving of energy, for in this case the additional energy, being supplied from a water power plant, would cost nothing, as in lessening considerably the capacity of power house required for any particular service. Two tons going down the grade will pull one ton up the grade; it is therefore necessary only to supply power for the tonnage up grade in excess of the down grade tonnage; with a system of train dispatching having this in view, a material saving can be made.

W. S. Murray: Law or economy brings electrification of railroads. It is peculiarly interesting, too, to note how economy hugs up to law, if law has been the cause. After law has had its turn, then comes the turn of the engineer. Such conditions may be levied by the law as to make impossible the opperation of a certain piece of railroad mileage as economically by electricity as by steam. It is the duty of the electrical engineer to choose such a system consistent with safety and the guarantee of continuity of service, which will increase to a minimum amount the original operating expense. When economy dictates the electrification, again it is the duty of the electrical engineer to elect a system consistent with safety and continuity of service, which will decrease to a maximum extent the original operating expense.

The closing sentence of Mr. Armstrong's paper is:

> The keynote of electrification is capacity; by approaching the problem from this standpoint only can full benefits be obtained.

I am in full agreement with Mr. Armstrong on this score, except I feel that while he has furnished the horse, there has been no mention of the carriage and what the carriage contains; in short, I should have said the keynote of electrification is "ton-miles", then capacity to handle it. The track capacity of a railroad is tremendously enhanced by electrification, but ton-miles must be on hand to make necessary the increased locomotive capacity.

I cannot escape a decided exception to Mr. Armstrong's reference, "Petty economies effected in coal consumption and cost of locomotive repairs". Examining the principal heads under operating expense, we find "maintenance of way and structures", "maintenance of equipment", "conducting transportation and "general expenses". There is little choice in this list that electrification can detach upon which to practice its economies other than fuel and locomotive repairs. Of course the inference concerning the general increase of track capacity and operating facility, together with the fact that electrified lines offer more inducement for traffic in general, is not lost, but I cannot withhold figures that have come within my personal observation and keeping, which have a value keenly *important* rather than " petty " and, indeed, point directly to and are a demonstration of the keynote to electrification; namely, ton-miles.

In a previous contribution to the Institute's TRANSACTIONS in connection with the Stillwell-Putnam paper on the substitution of the electric motor for the steam locomotive, I presented figures that were worked out in a faithful effort by all concerned in it to secure what could be absolutely relied upon as the resistance of the main line of the New York, New Haven & Hartford Railroad Company between New Haven and Woodlawn. I shall briefly say in regard to this work, that after days of careful indication of steam locomotives on east- and west-bound runs with trains of varying weight for express and local-express service, the resistance for these several conditions was obtained, and the real relations between the ton-mile, the pounds of coal per ton-mile, and the horse-power-hours per ton-mile, were established in figures, upon which has been based the power house capacity necessary to operate the electric trains of the New Haven road. This effort was made to secure the actual service conditions rather than to depend on hypothetical resistance curves, the opinions on which are conspicuous for their wideness of variation.

Generating, transmission line, and railway equipment efficiencies are too well known not to be able, having determined the rim horse power required for propelling trains, to figure back to the power house the amount of the kilowatt capacity required to operate a predetermined schedule of trains. We cannot afford to quarrel with the machine efficiency of the steam locomotive. It is the equal of the machine efficiency of the electric motor morning, noon, and night. We shall take issue, however, on the efficiency which lies behind the two engines, viz: the generation of steam in the boiler of the locomotive versus its generation at the power station with its attendant transmission and conversion into electricity for application to the motors driving the locomotive.

The following table shows the saving of fuel which will be effected on the New York division when all freight and passenger trains, now operated by steam, receive their draw-bar pull by the electric method of traction.

	Ton-miles per annum	Tons of coal steam traction	Tons of coal electric traction	Cost of coal steam traction	Cost of coal electric traction	Saving of electric over steam traction
Express...............	592,240,000	57,447	29,870	$183,830	$89,620	$94,210
Local-express........	348,000,000	58,300	28,600	186,560	85,800	100,760
Freight..............	2,223,000,000	187,844	139,010	563,520	417,030	146,500
	3,163,240,000					**$341,470**

In connection with the work done in the field to secure the data as compiled in the table just read, a diagramatic tabulation of the observations considered pertinent to the test was made,

SHOWING
- Average cut-off variation
- Boiler pressure variation
- Water consumption
- Indicated horse power
- Grade profile.

Ten locomotives were included in this test, and eighteen days of consecutive observation of performance were utilized.

Briefly, this diagram indicates that in express work 2,055 indicated horse power-hours are developed in the evaporation of 57,594 pounds of water, giving an average, therefore, of 28 pounds of water per indicated horse power-hour; and on local trains this figure is slightly increased, the evaporation being 42,987 pounds of water for 1,435 horse power-hours, making the rate, 30 pounds of water per indicated horse power-hour. I mention these figures, as we are all familiar with the turbine guarantees of 20 pounds of water, including auxiliaries, per kilowatt-hour at the switchboard which, reduced to a horse-power basis, would be 15 pounds of water as measured at the switchboard. Remembering the ratio of 7 to 10 in the evaporation of locomotive vs. stationary boilers per pound of coal, it is not a stretch of conscience to concede that twice the draw-bar pull can be developed by the electric method of traction for coal burned under the boilers of stationary plants vs. coal burned in the fire-boxes of locomotives.

In that contribution, I also submitted figures bearing on the cost of repairs and maintenance of 20 steam, freight, and passenger locomotives; these have been kept most carefully over a period of one year and showing 8.1 cents per locomotive-mile for freight engines and 5.6 cents per locomotive-mile for passenger engines. The engine mileage of the New York division of the New Haven road amounts to about 4,836,992 miles. This mileage is divided for passenger and freight service into 2,993,328 and 1,843,664 miles, respectively. These figures were based on week ending October 25, 1907, and it is to be noted that it will, therefore, be below the average, on account of the summer months bringing the heaviest traffic. This means an operating cost of $316,962.00 per annum, for the maintenance and repairing of engines.

The average figures that I have been able to secure on electric engine repairs per locomotive-mile are about 2 cents. Increasing this figure 25% for safety and assuming the same number of electric engines replacing steam locomotives, (as a matter of fact there would be less electric engines required on account of the greater mileage per diem derived from electric locomotives) the total would be $120,924.00 per annum, showing a saving over steam locomotives of $196,038.00. Therefore, the net saving on fuel and locomotive repairs in favor of electrification gives a round sum of $562,470.00 per annum. This, upon a capital basis with money at 5% represents $11,249,00.00, a rather effective credit on the expense necessary to invest.

Messrs. Stillwell and Putnam's exhaustive and comprehensive analysis of the statistics of railroads for 1904, compiled by the Interstate Commerce Commission, and proof sheets of the report of the Commission for the year 1905, give the undeniable records of railroads of this country; and the averages for over five years, as shown in the paper read by them before this Institute, show fairly and honestly, where and where not economies may be effected. Of the four principal headings of operating expense as mentioned before, two of them, viz.: "maintenance of way and structures" and "general expenses" may be equated. Of the remaining two, viz.: the "maintenance of equipment" and the "conducting of transportation," the first of these indicates that operation could be effected by electricity at an expense of about 63% of that of steam; and of the 37% saved, 75% of this is on account of the economies in the repairs of electric vs. steam locomotives. Our steam experience, to date, enables me to confirm these figures of Messrs. Stillwell and Putnam.

Concerning the second item, viz: the conducting of transportation, which is generally the largest item in the operating expense of any railroad, it is to be noted that the estimated cost of operation by electricity is 79% of that of steam; and it is safe to consider that of the 21% saved, 90% of this is on account of fuel and round-house expenses. These figures are confirmed by the practical investigation which I have been conducting in an effort to secure the relative operating costs of the New York Division by electricity vs. steam.

Mr. Armstrong's paper is full of a most interesting line of initiative, and is particularly attractive to me on account of the broad scope in which he has handled this subject. The matter of fuel and locomotive repairs, has been one of such interest to me that I must ask the indulgence of the Institute in having dwelt with such length on these two details, from a paper which has covered so much other ground.

I may say that I almost regret to see the disappearance of the steam locomotive from the electric zone of the New York, New Haven & Hartford Railroad, as contrasts in operation are never better seen than when they are almost inseparately attached to each other.

In closing, I would refer to two details in operation, which unquestionably increase the capacity of a given trackage for trains operated by electricity, viz: yard switching, and turning of engines at terminals. I believe it is safe to say that our experience, to date, has demonstrated that in the first instance double the amount can be accomplished in the same time; and in the latter, electric engines are ready to make their reverse train movement in 25% of the time required by steam locomotives, assuming that the water-tanks, ash-dumps and turn-tables, are within the yard limits of the terminal.

Wm. McClellan: We shall not be able to state positively what basis there is for electrification on the score of reduction in operation charges until we have a complete engine stage equipped electrically, with no steam locomotive shops, no steam repairs, no unnecessary buildings, but everything equipped to handle electrical equipment only, in the most economical manner. For this reason I think that the speaker of the evening has taken the proper view, when he bases his whole argument on capacity. He believes that heavy grades will prove the most firuitful field in which to start, and we must agree with him very heartily. It cannot be gainsaid that he has proved his case so far as this point is concerned in this paper. It should not be forgotten that all electrification to date has included a very great change in operating conditions and frequency of train service. As a result, electrification has been charged with many expenses which properly belong to amplification of the service and not to electrification proper. To get a just comparison in such cases it would be better to estimate what it would cost to give the increased service, both in quantity and quality, by steam locomotives, and compare this with the estimate required to do the same work by electric locomotives. In most cases I believe it would present the case for electrification in a much more favorable light than the way it is usually done.

I must also agree with the author that the electrification problem is not a substitution problem. It involves taking the traffic problem of the railroad and solving it along wholly different lines, from wholly different points of view. An electric locomotive is not something that is designed to replace a steam locomotive taken off rails. It has different capabilities,different possibilities, and these must be considered as influencing the whole traffic problem. The very greatest stress should be laid on this point in discussing the matter with our steam locomotive friends.

C. L. de Muralt: My belief is that, when one or two of the large railroads will have been electrified, we shall find economies in operation to have slipped in, with or without intention. But the largest electrification work in the near future will likely be done for the reason that very much more traffic can be handled over existing tracks with electric locomotives than with steam locomotives. My office has recently had occasion to work out a problem where a road with something like eighty miles of double track was actually nearing the end of its ability to handle traffic with steam locomotives. The question came up of adding new tracks to increase its capacity. In this case, there would have been two additional tracks which would have cost something like $15,000,000. On the other hand, a complete electric equipment for the old tracks, comprising power stations, distributing system, and locomotives, will cost only about $3,000,000. The handling of the present amount of traffic by electricity will save in operating expenses something like $200,000 out of $800,000 and with the electric equipment pushed a little harder, there will be a chance to increase traffic forty to fifty per cent, over what the tracks will stand under steam. Here, therefore. is a case where electricity should be used and electric equipment installed just as soon as the $3,000,000 can be raised.

Mr. Armstrong has not only reaffirmed that increase in capacity is the keynote, he has also shown us what he understands by capacity and what we all should understand by that term. It is a pity that so many engineers, who have to draw comparisons between electric and steam locomotives, are not quite clear on this point, and that comparisons have been made which are really quite a little misleading. It is not so much the tractive effort or the draw-bar pull which a locomotive can give, but the speed at which that draw-bar pull can be developed, which is important. And that is what Mr. Armstrong so nicely points out, when he defines as capacity, not merely draw-bar pull, but the product of draw-bar pull times speed. From this viewpoint Dr. Hutchinson's statement will look different. If I understand him correctly, he believes that steam locomotives could give about 9,000 lb. draw-bar pull per axle, while no electric locomotive could be built to do the same. Personally, I am absolutely convinced that electric locomotives can do better than that. But, even if an electric locomotive could give only 4,000 or 5,000 lb. draw-bar pull per axle, but can carry that 4,000 or 5,000 lb. up to three or four times the speed at which the steam locomotive can develop 9,000 lb. draw-bar pull, cannot the electric locomotive handle more traffic? In other words, is not its actual capacity much larger than that of the steam locomotive? As an illustration I have in mind a high-speed steam locomotive of the New York Central Atlantic type, which weighs about 160 tons, and develops a tractive effort at 45 miles per hour of about 13,000 lb., while the New York Central direct-current locomotive weighs about 95 tons, and will carry at the same speed of 45 miles an hour a tractive effort of about 14,000 lb. In the one case about 80 lb. per ton, and in the other about 150. A European type of three-phase electric locomotive weighs about 70 tons and will carry at 45 miles an hour about 23,000 lb. of tractive effort, which is a still better showing. In short, I believe the question raised by Mr. Armstrong, and the solution offered by him, both show clearly what we are likely to come to: those lines will probably first be electrified which, with steam as motive power, are now at the limit of their traffic capacity. Electricity will show that for a comparatively small expenditure of money we can increase the traffic of such lines considerably, and I think we may look to an early use of electric locomotives for such purposes. That type of electric locomotive will in the end prove to be the most useful, which in a given unit weight is able to concentrate the greatest amount of tractive power.

W. N. Smith: There is very little to add to what may be called the statistical feature of Mr. Armstrong's paper. He has had exceptional opportunity to go into such parts of the relative costs as are covered by the scope of his paper. But the problem is so complicated that the part of it which has here been covered in some detail does not cover the whole question. I agree fully with those who have remarked that the items which he has called petty or incidental are of considerable importance. They depend, of course, on the conditions of the particular road which the engineer may be called upon to investigate. A mountain road, or a road with a continuous long pull of 20 or 30 miles up-grade, is a different condition from a broken profile, or a level profile, such as the road from which Mr. Murray has given some figures. It is a very interesting proposition to consider the total resistance to be overcome in drawing a train over a line, and it is a relatively easy matter to consider it from that standpoint when the road is almost absolutely level; but when a large amount of drifting comes into play, with long down-grades, or with a broken profile, the problem becomes somewhat more complicated. It is very true that the whole question focuses upon capacity; but there are several different ways of looking at capacity, and one of the aspects that has not to my knowledge been given very much consideration in most of the communications on the subject, is the *capacity for train movement* of any given piece of single-track railroad. This is really a deep question. It is one that railroad operating men are daily in contact with, and it is to them that any question of capacity must appeal first. They are the men whom, first of all, you have to convince that you can increase the capacity of a piece of track, and while the possibilities of double track, as to increase, are considerable, the possibilities of single track are considerably less, particularly if the profile is undulating and operating conditions generally are difficult. It is quite conceivable that it would be found impracticable to get as many trains over a given piece of single track as would be required to make it a financial object to electrify that particular section. In such a case, of course, electrification would be reduced to an absurdity.

I mention this simply as a possibility. I have not had opportunity to examine a particular instance of this type carefully enough to define where it would begin to be an absurdity, but I know that such a consideration is apt to be present, and cannot be left out of the calculation. The operating man's standpoint is of the greatest importance, and it is one, I fear, to which many electrical engineers have not hitherto given sufficient consideration. The general trunk line electrification work of the future, however, must be considered from that standpoint.

I suppose that considerably more than 75 per cent. of the mileage of the railroads of the United States is single track, and the cost of increasing the capacity of these roads by double tracking them, in order to enable much greater number of trains to be run over the road in both directions, would stagger the imagination if it were estimated. Electrification is in some respects a simpler proposition to estimate on, in so far as cost is concerned, but there is no use trying to figure out how to run more trains over a piece of road than the road will accommodate. The questions of block signaling, turn-outs, and train-dispatching must enter into the problem first of all.

The capacity of the steam locomotive has been mentioned as being in some instances greater than could possibly be obtained continuously from an electric locomotive, but it occurs to me that this will depend to some extent on the conditions under which the steam locomotive is to operate. We know that up-grades of 30 miles or longer actually exist where a steam locomotive working at full power has to stop for water on the way up; of course it can go right along again at its maximum capacity after it has filled its tender, but when it has worked up to the point where all its water is exhausted, the locomotive must stop to have the supply replenished; and to that extent there must be some qualification to statements regarding the uniformly high capacity of a steam locomotive.

The question of load-factor has not been touched upon in the discussion of the cost of power. I will not undertake to discuss it, except to state that it seems to me rather an important matter to consider in making an estimate of what the cost of power will be in predicting the economic performance of an electrified section. Of course it goes without saying if the section is congested the load-factor will be high, but if the trains are few it will not be high and the cost per kilowatt will run up.

The weight of the tender has been mentioned, and any one who will examine the general data of the heaviest steam locomotives now being turned out will perhaps be somewhat surprised at the enormous weight of the tender, a dead weight, which, though a part of the motive power, cannot produce any tractive effort.

It is probable that a comparison with the consolidation type of steam locomotive will show a greater economy for electric power than will a comparison with the Mallet type of locomotive, which is said to be very successful in mountain work.

The various items of cost, even those called "petty", which enter into locomotive operation and maintenance, whether steam or electrical, are so variable that differences of a comparatively small number of cents per locomotive mile in a few items may make a large difference in the showing that the final tabulation will produce, and may throw the balance one way or the other, and every possible item of expense must be taken into consideration making a comparison that will pass as valid when presented to the practical railroad operating man.

Chas. P. Steinmetz: The leading conclusion of Mr. Armstrong's paper seems to be that the advantage resulting from electrification is to be found in the increased capacity; that is, the ability of the road with the same trackage to handle a greater amount of traffic. This, however, means that the change from steam power to electric power is not a mere substitution of the electric locomotive for the steam locomotive, but a readjustment of the ways of operation; that is, an increase of the speed of operation of freight service by taking advantage of the feature of the electric locomotive to be able to carry its draw-bar pull up to a higher speed. We usually find, when introducing a more advanced way of doing a thing, that we have not a mere substitution, but to get the greatest benefit from the change, the method of operation must be rearranged. So nearly a century ago when the stage coach was replaced by the steam engine, the first attempts to attach the steam engine to the stage coach and pull it over the country roads came to naught, and steam propulsion became successful only by putting the locomotive on the railway track. Characteristic of the steam locomotive is that it is essentially a constant power motor. It gives approximately the same power whether running at high or low speed. The draw-bar pull, therefore, does not tell the whole story, but the limit is the steaming capacity of the boiler, and the faster you move the oftener you fill the cylinders, and since you cannot for a long time exceed the ability of the boiler to produce steam, you have to cut off earlier, and so get less draw-bar pull. Not so in the electric motor; in this the limitation essentially consists in the constant loss of power. The limit of the electric locomotive is that it must lose only so much power in the motor, in the general average, as to be within safe heating limits. Since efficiency rapidly increases with the speed, it means you can get more power out of it at higher speeds, up to a certain limit, and therefore the electric locomotive is best at higher speeds than the steam locomotive, and we have to take advantage of this feature if we desire to show the best results. It, therefore, as you see, does not mean a mere substitution, but also means a readjustment especially of the most important part of the railway service, the freight traffic, for higher speed. Higher speeds necessarily mean increased capacity of the system, even without any increased draw-bar pull, even with less draw-bar pull, and in this feature I believe lies the main advantage of electric traction; but it makes it necessary to readjust the method of operation to the changed condition of railroad motive power, to get the best results of the electric locomotive. You may merely substitute, but you get better results by not merely substituting, but also by increasing the speed to operate at the most economical speed of the electric locomotive, and this in general is higher than the most economical speed of the steam locomotive.

A. H. Armstrong: In working up the comparison of the performance of the steam and electric locomotive I was impressed with the fact that the greatest benefit to be secured seemed to lie in the electrification of mountain-grade divisions. That is, the greatest necessity for electrification as well as the greatest return for the money invested are met with on heavy grades, and I am, therefore, very much pleased to find that the economy figures given by Mr. Wilgus as obtained in actual service on the New York Central check up in some degree the final results I have arrived at by calculation. Also the calculated figures by Mr. Murray for another section of a level road, New York, New Haven & Hartford Railroad, indicate also a comfortable return upon the capital required for electrifying the New York division of that road. With these figures for level operation it would seem as if my general conclusions for the electric operation of mountain-grade divisions were very conservatively arrived at.

In regard to the remarks of Dr. Hutchinson, that a total draw-bar pull or tractive effort of 9000 pounds could not be continuously sustained by an electric locomotive, I have only to point out two or three facts of operation which may perhaps have been overlooked by him in making the statement. With 50,000 pounds per axle and a tractive effort of 20 per cent., which is conservative for average conditons of track, 10,000 pounds of tractive effort is available. In practice, however, it is not possible to work any locomotive at this tractive effort continuously irrespective of its type of motive power, owing to the broken character of all profiles, as even on mountain-grade sections crossing a continental divide the grades are not uniform, but the average grade is seldom more than 60 per cent. of the maximum or ruling grade. For example, the greatest extent of continuous grade in this country is on the Sacramento Division of the Southern Pacific system, which has a 1.54 per cent. average grade for 83 miles with a ruling grade of 2.2 per cent. In other words, during the rise of 7000 feet in 83 miles the average grade is 70 per cent. of the ruling grade. A locomotive operating over this division will be called upon to sustain, say, 60 per cent. of its maximum tractive effort, thus leaving a margin of 10 per cent. over the demands of the ruling grade in order to start up the train on maximum load and grade conditions. Under these conditions the electric locomotive would not in any way suffer in comparison with the steam locomotive, as the heating of the motive power would not in any way prohibit the delivery of 6000 pounds per axle at any speed that may be safe in operation. Furthermore, it is necessary to take into account the very serious delays occurring on single-track roads where the traffic may be heavy; so that all operating conditions considered, I see no reason why it should not be possible to keep the temperature rise of the electric motive power well within safe limits in practice.

In choosing the word "petty" I seem to have been particularly fortunate in irritating Mr. Murray into giving some very valuable data pertaining to tests made by him on the

New York, New Haven & Hartford tracks with steam locomotives. Mr. Murray's figures are going to prove very interesting reading when we have a chance to go into them in detail at greater leisure, but I am surprised to see that such a low steam consumption (28 to 30 pounds per i.h.p. hour) was arrived at in actual tests. This steam consumption could be looked for by indicator, but it seems rather low if it includes all the stand-by losses of the locomotive not in actual operation.

In dealing with steam locomotive statistics I have found it necessary to divide the determination of coal and water consumption into two parts. First, that required for the actual hauling of the train; secondly, that lost while coasting or standing still. For instance, I show in the paper that on a certain road there are some 400 pounds of coal and 4000 pounds of steam used per hour while locomotives are idle at terminals, turn-outs, or coasting down grades, while the performance of this simple consolidation engine when actually hauling a train corresponded to a steam consumption of 28 to 30 pounds per boiler horsepower-hour with an evaporation of approximately six pounds of water per pound of coal. The Mallet Compound requires more coal than this chargeable to stand by losses, and further requires the admission of steam in order to coast down grade at a speed much higher than 10 or 12 miles an hour. All of these losses in steam locomotive operation amount up to a grand total that in many cases will show a considerable excess cost over the cost of electric power for hauling the same tonnage with electric locomotives. Hence my feeling that the figures submitted by Mr. Murray are somewhat low for the total coal and water consumption of the locomotive for twenty-four hours in regular service.

I must adhere to my position taken in the paper that economy of operation as regards coal consumption does not constitute any sufficient cause for electrification in the great majority of cases, and I think we cannot bring out this fact too strongly. It is not sufficient to show the management of steam roads that they can get a return of 10 per cent. or even 20 per cent. upon $10,000,000 or more required for electrification, as they are not looking for investments of this character. Careful consideration, however, will be given to any report showing means of increasing gross receipts or that will offer a reliable substitute for the double tracking that may be necessary to provide for a rapidly increasing tonnage. I must adhere, therefore, to the idea that the main reason for electrification of roads other than terminals, tunnels, etc., is embodied in the increased capacity of the electric locomotive, providing increased tonnage capacity of the tracks, decreased running time, etc.—all of which guarantees an increase in gross receipts and a possible saving in expenditure for additional tracks, reducing ruling grade, etc. That this electrification will be accompanied with a gratifying reduction in operating expenses is a still further argument for replacing the steam locomotive, but it is not of sufficient importance in itself in the majority of cases, to encourage electrification.

I note the doubt expressed by Mr. Smith as to the saving effected in the electrification of single track roads, and would state that it is on just such roads as these where the greatest saving can be effected both in cost of electrification and in operating expense. A large volume of traffic is carried over a single-track road under the greatest difficulty and at considerable expense. This applies especially to trains hauled by steam locomotives which are capable of only six or seven miles per hour schedule speed up severe grades, and add considerably to the number of signal stops by reason of their limited radius of action with their coal and water supply. For instance, a steam locomotive working at an average of 75 per cent. of its full boiler capacity on a mountain grade cannot cover more than 15 to 20 miles without taking on more water, in this respect very much resembling the electric automobile forced to return frequently to its charging station for the material for a fresh start. It is entirely safe to say, therefore, that the total tonnage capacity of a single track will be very much increased with the adoption of the electric locomotive, and the cost of such electrification in some cases may be considerably less than the capital required to double track or duplicate the single track already installed. In other words, where a mountain-grade division has reached the maximum tonnage capacity possible with single track, and it becomes a question of double tracking with steam locomotives, a careful analysis of the conditions may show that electrification of the present single track may be accomplished with a lesser expenditure and be followed with a greater return upon the money invested.

I agree with Dr. Steinmetz in the views expressed by him and would draw the attention of the members to the entire revolution in methods of handling short-haul passenger traffic by the introduction of the electric motor. I believe also that the introduction of the electric locomotive will bring about fundamental changes in the method of handling freight traffic by reason of the many inherent advantages enjoyed by the electric locomotive and not shared by its steam competitor.

W. S. Murray (by letter): In answer to Mr. Armstrong's question as to whether the coal measurement was made for the full 24-hour day, including the hours during which the engine was not doing revenue work, such as time spent in the roundhouse, over ash-pits, cleaning fires, etc., I would say that this was the case; the idea not being simply to get the rate of coal per horse power-hour while the engine was making its revenue runs, but to secure the real commercial rate or day consumption, which governs the bill the railroad company pays.

DISCUSSION ON "TRANSMISSION LINE TOWERS AND ECONOMICAL SPANS" AND "LIGHTNING-RODS AND GROUNDED CABLES AS A MEANS OF PROTECTING TRANSMISSION LINES AGAINST LIGHTNING," AT NIAGARA FALLS, N. Y., JUNE 26. 1907.

(Subject to final revision for the Transactions.)

William Hoopes: The method of treatment of this problem appears so excellent that one is at once interested in its practical application. The first conclusion reached is that the economical span-length is determined, not by the original cost of the line, but by its annual cost.

The annual cost is made up of three items:

1. Interest and depreciation on the first cost.
2. The cost of repairs and patroling.
3. The money damage from interruptions to the service.

If lengthening the span will reduce the number of interruptions and cost of repairs, then the economical span is longer than that which gives the lowest first cost.

Inquiry into the operation of a large number of transmission lines reveals the fact that by far the larger portion of the interruptions of service is due to trouble occurring at the point of support; this applies particularly to steel-tower lines. Reduction of the number of supports does, therefore, reduce the annual cost.

The paper shows that this particular line on 800-ft. spans would cost about $300 more per mile than if on 400-ft. spans. Interest and depreciation on this at 10% would be $30 per year. Halving the number of supports would probably save much more than this.

I believe the subject has not been treated in this way in this or any other paper, so I should like to suggest to the committee that such a paper would open up a very live topic.

However, the province of Mr. Scholes' paper is really to show the least first cost of the line, and the above remarks are not strictly germane to it. Investigation of its practical application leads to the following queries:

1. Is the assumption of a uniform price per pound justifiable?
2. Does the retention of the same geometrical figure permit the design of all the towers for the least cost?
3. It is fair to assume that large foundations for higher towers cost as much per cubic yard as small foundations for low towers.

The cost of a tower to the purchaser is made up of the following items:

1. Cost of steel and transportation.
2. Cost of shop work.
3. Cost of galvanizing.
4. Cost of erection.
5. Manufacturer's profit.

If the cost of the tower is directly proportional to the weight of the steel, then all of the items of cost must vary at the same rate as the weight. The cost of the steel does vary approximately as the weight.

The paper gives the cost of a 34.5-ft. tower as $30, and of a 70.5-ft. tower as $243, which is about proportional to the cubes of the heights. The other costs should therefore be as the cubes of the heights.

Inquiry from a concern which makes a very large number of towers elicited the following opinions:

1. As the number of parts is the same for large as for small towers, the number of shop operations will be about the same; but as the shop operations will be slower on the heavier work, the shop cost will vary about as the height of the tower.

2. The same opinion was expressed with regard to the cost of erection.

3. The galvavanizing cost is approximately proportional to the superficial area, or to the square of the height. The galvanizing was said to be a very material portion of the whole cost.

When it came to a question of manufacturer's profit the source of my information ran dry, but if it increases as the cube of the height, it would seem to afford a considerable opportunity to a resourceful purchasing agent.

From the foregoing it would seem that all the costs which go to make up the cost of the tower, other than the cost of steel, vary at a less rate than the cost of the steel, and that a smaller price per pound should be used in determining the cost of the large towers than is used for the small towers.

It would add to the value of Mr. Scholes' paper if he would answer my three questions, and I should like to ask further if it is actually possible to furnish a 34.5-ft. tower galvanized, for $30? or a 32-ft. tower for $21? the prices given by the paper.

P. H. Thomas: Mr. Rowe has given us valuable data on the effectiveness of the overhead ground-wire for protecting high transmission lines. The only thing that remains is to draw correct inferences from the data, and that is very difficult to do. There are some salient points, however, which seem to indicate the real lesson of the paper.

In the first place, in judging of the performance of a new line, the necessary elimination of weak insulators which occurs during the early operation must be taken into account. Mr. Rowe says that by the use of a series transformer in the ground connection he has discovered a way to get the current off the line quickly enough not to break the insulators, so that the power could be thrown directly back again. This is an important point to consider, for if that is the way the improved operation was brought about it is no credit to the overhead grounded conductor.

Mr. Rowe says further:

> On several occasions grounds came on the lines during lightning storms and the power was immediately cut off in order to clear them. In general, these grounds could not be located, so it cannot be said that

lightning did not go over the surface of the insulators on the section where the grounded cable was in place.

This apparently indicates that, only improvement resulted from the grounded wire.

Furthermore, in addition to the installation of the grounded cable, there was a change in the size of the insulators, largely on that part of the line protected by the overhead cable. This, in itself, is the very best sort of lightning protection. As Mr. Rowe himself intimates that the original insulators were really too small for their work, it will not be safe to infer too much from the increased satisfaction in the operation after the introduction of the grounded overhead conductors. On the other hand, it is probably certain that the overhead grounded conductor does relieve the line insulation a great deal; especially in the way of reducing the severity of the heaviest strains.

Is it not true that too great a risk is being taken in using steel poles, steel cross-arms and pins, relying wholly on the insulator? It is relatively easy for a charge to pass over the insulator's surface to ground at the pin, and it is usually destructive when it does come, starting an arc to ground which breaks the insulator and tends to shut down the plant. Is there not some way to preserve the advantage of the old wooden pin and cross-arm, which prevented many discharges to ground from becoming short-circuits?

W. S. Lee: As Mr. Hoopes has suggested, we should not try to get too economical a tower or too economical a span. In some cases these transmission lines are carried over a rolling country; in other cases over a flat country with no fall for a water power, so we have to span from hill to hill, and from point to point, and the practical erection of the line means irregular spans. We have found that in our service. Now, while one may figure on a fixed-span tower, the chances are that the spans will be regulated by the topographical conditions. The usual practice is to make a profile of the country. If there is to be a tower for a 400-ft. span, and the next span has to be extended to 550 feet or 650 feet, we would need towers of different strength. It would be best to keep the tower standard on the line, in case of repairs, or shipments of parts; and for that reason I would suggest getting stronger towers which could be used for either long or short spans.

Referring to Mr. Rowe's paper: In 1897 I was with the Anderson Water Light & Power Co., Anderson, S. C., and we built an 11,000-volt line for a distance of 10 miles. While the poles were being constructed, and before there was a wire strung on them, two poles at different points were shattered entirely by lightning. The plant was built and has been in operation since that time; it has two lines of barbed wire overhead. Though there has been some trouble with lightning, they have not had a direct stroke of lightning on that line since that time. The Catawba Power Company, of Charlotte, N. C., has a transmission system of 18 miles. When the line was built in

1904 one pole was struck by lightning, but there was no wire on it. There is one grounded wire overhead, and no pole has been damaged by lightning since that time, nor has there been a direct bolt of lightning.

We built in 1905 at this same station, a line 20 miles long. It had 11,000-volt service, built with 40,000-volt insulators. This was a three-phase, single-circuit line, and in order to arrange for equilateral triangle construction one wire was placed on top of the pole. We endeavored to locate a grounded wire above the apex wire, by extending supports up to this point, and curving them so as to keep away from the apex wire. This arrangement did not work. We found that irregularities in the country resulted in a tendency to pull up or down, in some cases to bring the grounded wire close to the apex power-wire. For this reason the grounded wire was left off this circuit. Since 1904, there have been two direct strokes of lightning on this particular circuit; neither stroke interrupted the service, but both damaged poles by splitting them. All the lines are now being equipped with the overhead grounded wire.

F. B. H. Paine: Mr. Thomas suggested a question which is frequently asked, in view of our extended use of steel poles and towers; whether we are not putting too much trust in the insulator, and would we not do better with the added insulation of pole, cross-arm, and pin? For a good while I was in doubt about it, but after an experience of two years I think that Mr. Mershon's judgment has been amply sustained. I have recently visited many transmission plants, and in every instance I found that the annual destruction of poles and cross-arms, that is, the entire destruction of the supporting structure, exceeded our loss of insulators per mile. We can replace the insulators much quicker and cheaper than we can the entire supporting structure, whether it be of wood, steel, or what-not. We have something like 200 miles of 60,000-volt transmission lines on wooden structures using the same insulators cemented on steel pins, the steel pins being carefully grounded. We have had some terrific lightning disturbances in that section, and, although many insulators have been lost, in no instance has any injury come to the wooden structure on account of the pins being grounded, and to all intents the same condition existed as on the steel tower or steel pole. I think we have answered the question as to the desirability of wood as an insulator for high-voltage lines very effectively: use metal pins, ground them, and save the pole and cross-arm.

C. W. Ricker: The experience of a railway transmission line in western Ohio may be of interest.

This consists of about 100 miles of three-phase, 3300-volt line built in 1901 on wooden poles with wooden cross-arms and porcelain insulators designed for use at that voltage by one of the largest American makers. Each cross-arm had two steel braces applied in the usual way, and the insulators are set on steel bolt pins about 9 in. long. The line runs through a country in which lightning storms are frequent but not exceptionally severe. Interruptions of service have occurred during thunder storms, and usually two insulators on the opposite ends of the same arm would be found punctured from the tie-wire to the pin. The interruptions became so frequent that it was necessary to make some change, which had to be done without disturbing the working of the line; this left about two hours each night available for work, and the owners of the line were not prepared to incur any heavy expenses. Accordingly, half the cross-arm braces were removed, leaving on each pole a brace from the pole to one end of the cross-arm only, and wooden pins about 15-in. long were substituted for the steel pins, using the same insulators.

After this change the interruptions of service due to lightning were diminished from an average of two or more a month to about the same number during the season following the change. Several cross-arms were burned off, but caused no suspension of service at that time.

Geo. T. Fielding, Jr.: Incidental to the main subject of Mr. Scholes' paper, I would like to arouse some discussion on one of his assumptions: namely, that of allowing for one-half inch of sleet upon the conductor. As a matter of common interest, it would be profitable to learn if any one here has ever seen sleet upon a transmission line that was carrying power or even charging current, and also if there was any wind at the time this occurred. This is an old question perhaps, but we have had experience enough now to cease basing calculations upon advance assumptions that were made for the first lines erected. The greatest mechanical stresses on transmission lines are due to high winds, and a small increase in the diameter of the conductor, as occasioned by a coating of sleet, results in a considerable increase in the imposed stress. The assumptions made, as regards sleet, therefore very materially influence the allowable sags and tower-heights, and while it is legitimate to favor conservatism, it is questionable if we are not inclined to be over-liberal.

I noticed that Mr. Rowe uses a stranded steel cable for the ground-wire. This has been the practice on a number of lines. On account of its short life and tendency to stretch and sag, one of the larger telegraph companies has recently ceased using stranded cable for guy- and messenger-wire service. The old solid No. 3 steel galvanized wire is now being substituted in its place. It seems quite reasonable that the cable should tend to retain moisture, by virture of its strands, and hemp center if it has any. This moisture is not helpful in preserving the metal against rust.

Mr. Rowe seems to have had considerable trouble with puncturing of the insulators. This experience has been repeated on many other transmissions. On steel-tower lines where disturbances cause local and suddenly excessive potentials or frequency, the insulators are often observed to puncture before they will arc over, due probably to the element of time which is necessary for the potential to distribute itself.

Increasing the thickness of porcelain does but very little toward increasing its resistance to puncture. It appears as if the use of larger insulators is not the solution of the problem; that is, it is not enough simply to install insulators of larger dimensions, insuring merely a greater arc-over capacity. It is essential to separate the live conductor and the ground, the pin, by a greater distance than has heretofore been specified to obtain reliable insulation: this has been accomplished by the suspension method, described in the paper by Mr. Hewlett. We shall be compelled to direct our efforts with this principle in view before we can successfully operate at, or above, 100,000 volts.

N. J. Neall: One point in Mr. Rowe's paper is, in my judgment, misleading; that is, the use of a circuit-breaker attachment in the neutral of the transformers. In any three-phase transmission line with grounded neutral, the puncture of even a single insulator is more than likely to result in the fusing apart of the conductors, so that in this particular instance any disturbance of this character would undoubtedly seriously impair the continuity of service. I have seen this fusing take place in suprisingly quick time and realize perfectly what it means on service. Now the conclusion to be drawn from Mr. Rowe's paper is that the additional line protective apparatus, irrespective of the automatic cut-out, has been the chief benefactor in this case, but this seems to me a very doubtful conclusion. In other words, the important result is that a *combination* of these things, overhead—ground protection, larger insulators, and automatic cut-outs, have produced the desired improvement.

Ralph D. Mershon: The assumptions as to sleet, wind, and various other things which should be taken care of in the design of a transmission line are questions on which engineers will differ almost as much as on the subject of the use or non-use of choke coils. It seems to me that the general solution presented by Mr. Scholes is a very admirable and satisfactory one. There are some points in it to which exception might be taken, but if all the refinements are gone into, such general solution would become so complicated that its value would be questionable. The value of this general solution is that by sorting general assumptions, one can arrive at a preliminary idea as to what is going to be the best plan, considered from the standpoint of those assumptions, and that this preliminary idea will serve as a guide in adapting the construction to meet other considerations, such as inequalities of the country, the desirability of having fewer points of support, etc.

I shall be interested to hear from Mr. Scholes as to the cost in proportion to weight.

Mr. Rowe's experience with grounded wires does not enlighten me much. It does not seem to me that he has offered any definite evidence that the grounded wires do a great amount of good. In the plant of the Niagara, Lockport and Ontario Power Company, we are trying to avoid the use of the grounded wire on account of the expense of putting it up. We are installing on the top cable—there are only three cables, carried on the tower in the form of an equilateral triangle—what amounts to a horn lightning-arrester, a grounded horn reaching far enough above the tower to serve also as a lightning-rod. During the last few days we have had worse storms than we had last year, and the results, so far as we have been able to analyze them, seem to show that these line structure lightning-arresters, as we call them, have been of great value. Their value could be greatly augmented by increasing their number. They are now spaced at approximately 2200 ft., and are set for a discharge gap of 6 in. This discharge gap will be reduced to 4.5 in. or, perhaps. even to 4 in.

Some of our experiences seem to show that lightning does not travel along the line. During one of the storms the last two or three days, we have had three insulators punctured between two of the line structure lightning-arresters. The lightning chose to puncture an insulator rather than travel 550 ft. to go over the 6-in. gap. Possibly, when we reduce the size of the gap, we can cause the lightning to travel.

I am not much of a believer in the idea of being able to foretell what is going to happen in the matter of lightning, whether the prediction involves the nature and contour of the country or the apparatus concerned. We now have, I believe, about 400 miles of main line; 80 miles of this is in rough country, the rest of it is over country that is practically flat. In the flat country the lightning is at times perfectly fiendish, so that, if there is any connection between lightning and mountains, there is nothing on our transmission line to indicate that such is the case.

We do not transpose our lines. We had some transpositions, but found they could be taken out, and have taken out almost all of them. We intend to confine the line structure lightning-arresters to the top wire, in order that when it operates our service will not be interrupted; since, if there are line structure lightning-arresters on two or more of the cables, and two of them operate simultaneously, a short-circuit will result. Whereas, if the lightning-arresters are confined to one of the cables, and we have a resistance in the neutral of the generating station, the arc will clear itself without necessarily interrupting the service. If we transpose and endeavor to follow out this idea, the line structure lightning-arresters would have to be, in some instances, on the top cable and in some instances on one or the other of the cross-arm cables. It may be that, before we get through, we shall put line structure lightning-arresters on more than one cable; but, judging from the performance of the line structure lightning-arresters with a 6-in. gap and spaced 2200 ft. apart, as is the case at present, this will not be necessary. In the last three severe storms, one of which was worse than anything we ever had before, the present installation of line structure lightning-arresters has done much good.

The sub-station lightning-arrester equipment is the one which Mr. Stott has designated as the "totem-pole" equipment. There are nine horn lightning-arresters to each three-phase circuit, three to each conductor of the three-phase circuit. One of the three is set for a large gap and high resistance, the next for a higher gap and lower resistance, and the next for a still higher gap and that has a fuse. So far these arresters have afforded full protection. They have discharged frequently. There are no choke-coils.

N. J. Neall: In your line arresters do you get a continued arc because of the resistance in the neutral, or is it the customary charging arc which you get if you ground one leg of the railway system?

Ralph D. Mershon: We have the neutral grounded through a resistance, and think the line arresters will behave in a good deal the same way as the intermediate arrester used at a sub-station having an intermediate gap, and which has 1000 ohms in series with it.

D. R. Scholes: It must be borne in mind, in considering this problem, that it is impossible to choose a single set of assumptions which will be satisfactory for all lines. Varying climate, contour of country, and other varying conditions of this nature make it impossible. The making of such assumptions in the paper is incidental to the main object of the paper.

It is to be observed that the method pursued in the paper is first to derive an equation expressing the relation between the weight of a tower of given design and its height and strength. This expression is almost wholly accurate. An example illustrating its application to a practical case is then given. In the example certain assumptions are made use of. It is expected that such assumptions will, in each case, be made to suit the particular conditions that are being dealt with.

Most of the discussion, however, has had reference to these assumptions, and while it is not important that their accuracy be proved, the following may be said in support of them: It is assumed that the towers may be had at a given price per pound. This may not always be the case, but, within the range of ordinary practice, manufacturers are to be found who will contract for such structures at a given price per pound, before the size or strength of the towers has been definitely fixed.

It is assumed that the cost of a foundation will vary directly as its volume. The foundation cost will, of course, largely depend on the local conditions. Inasmuch, however, as the economical span will almost always be between 400 and 800 ft., and since the size of the foundation required will not change greatly between these limits, such an assumption seems admissible in the present instance.

The builder of steel towers for transmission lines is apt to find that the variety of assumptions regarding wind, sleet, factor-of-safety, etc., with which he has to deal is almost as great as the number of different engineers with whom he comes in contact. Each engineer seems to have a different set of natural conditions to meet. The severity of his assumptions seems to depend, generally, on how much money his company can afford to spend on towers. Now it is manifestly impossible to give mathematical expression, in advance, to factors which vary from causes of this sort. So the paper aims to put in the hands of the engineer in charge of line construction a formula which will show the effect on the tower-cost of any change in assumption he may contemplate, and which will make possible a simple solution for the economical span on the basis of his own assumptions.

Frank G. Baum (by letter): Mr. Scholes finds a shorter span more economical than is generally supposed to be the case. It would be of interest had he drawn two curves showing the cost of tower structures, one using his assumptions of sleet or snow on the cable at time of maximum wind velocity, the other with no sleet or snow. In a large section of the country sleet and snow need not be taken into account in the calculations.

Farley Osgood (by letter): Will Mr. Rowe please say whether with complete overhead grounded wire and lightning-rod installation, the use of time-limit relays on the outgoing transmission lines, is recommended, or whether instantaneous relays are preferred?

It is believed that a lightning-arrester installation about 75 miles from the power-station would help the system to a considerable degree, especially if the proper type of electrolytic arrester is used, which has been proved to be very efficient in cutting off the crests of surge-waves.

Would Mr. Rowe recommend the use of an overhead grounded wire on a wooden pole line, to be grounded at every pole by a suitable ground wire running down the pole?

DISCUSSION ON HIGH-TENSION TRANSMISSION PAPERS AT NIAGARA FALLS, N. Y., JUNE 26, 1907

(*Subject to final revision for the Transactions.*)

P. M. Lincoln: An inspection of some of the illustrations shows that there is a very apparent angle in the cables at the point where they are attached to the tower structures at the bottom of the gorge. This angle would indicate that the strain at that point is downward. I would like to know why this method of construction was used. It surely cannot be on account of relieving the supports at the top of the bank of strains due to a long span, because the strains in the cables must necessarily be increased by the amount of the downward strain at the point where they are attached to these structures.

F. B. H. Paine: The cables drop from the cantilever loosely to the river-edge tower on which they are dead-ended. The cantilevers support the weight, and the water-edge towers simply hold them out of the vertical sufficiently to prevent their hanging too close to the steep hillside.

P. M. Lincoln: It seems to me that exactly the opposite effect would be obtained by this construction, since the curve which would naturally fall would be made more abrupt by pulling down at this point.

F. B. H. Paine: The span across the river is quite independent of the slope-spans, and is dead-ended on each water-edge tower. The crossing is not a catenary into which the water-edge towers are inserted and steady the cables. It is three independent dead-ended spans; two almost vertical and one almost horizontal.

P. M. Lincoln: I do not see why it is necessary to attach to the towers at that point.

F. B. H. Paine: Mr. Mershon divided the crossing into the three spans to avoid the effects of tremendous winds in the Niagara Gorge—blowing both ways at once—and which unusual condition he feared would result in swinging the cables together. He wanted as short a span as possible and as close to the bottom as possible, to avoid the effects of the cross-winds on one span. I believe our experience shows that the effect of these winds was exaggerated by the "oldest inhabitant."

D. B. Rushmore: Some of Mr. Mershon's power consumers get their power from a single line, and I think it is open to discussion whether such a practice is justified. In the line construction shown, some pertinent questions arise; for instance, from the experience given in the paper by Mr. Rowe, it has been found necessary to put the top conductor below the others, and to run the ground wire in its place. I think that a similar change would be desirable here.

The questions at once arise, why are the wires on separate towers? Why is a single tower not used to carry both sets of wires? Under what conditions can one high-tension line near another be repaired while the other is in operation?

Mr. Buck shows a line construction for very high voltage and he puts both lines on the same tower. Can he repair one line if the other is in operation?

The wooden A-poles which Mr. Mershon shows have got to be replaced every eight years, we will say, but not all poles will last eight years. Every time a pole is replaced, the transmission of power is interrupted, and while at first the interruptions from this cause are not many, they finally become so frequent that customers grow impatient and new customers cannot be got. Under these conditions it seems to me that a single line transmission with a wooden pole construction is not economically justified.

H. W. Buck: Regarding the possibility of working on one line with the other line alive: in Fig. 2, with the tower grounded and with the circuit out of service grounded, I see no reason why a man should not safely work on that dead circuit. He would have the whole tower structure between him and the live circuit, and the circuits are quite a distance apart, about 20 feet.

J. B. Taylor: Mr. Nicholson's method of locating breaks, or more properly grounds, on high-tension lines is extremely valuable, the broken insulator being the trouble which is most often experienced. I think that the transmission system on which he has made his tests was fortunate in having a man who could take up work of this sort, possess the proper ingenuity to make the proper application for the particular trouble, and be on the ground when the trouble came; but I doubt if the average transmission plant will install the necessary switches and resistances and have the experts to locate troubles in this manner.

A plant that was started up about five years ago had a fourth wire installed on a three-phase system. The idea was that when one of the three wires got into trouble, a simple system of knife-switches could cut in the fourth wire, and everything would go along as usual. The line has had occasional trouble, but for one reason or another—either because the operating force did not feel sufficiently sure of the conditions to cut in the spare wire, or because they felt that the trouble was of such a nature that it was unsafe to attempt to resume service before knowing what the trouble was—the fourth line has not been used.

I have not checked the mathematical equations in the paper, but offhand it is not obvious why the reactances of the long and short sides of the loop should come out in the same ratio as the resistances. The inductive effect of the return current in the earth does not appear in the analysis, and under some conditions this appears to be an essential factor. However, the accuracy of the test locations shows the method to be right for average transmission line when the two sides of the circuit are separated by a few feet.

Without doubt Mr. Nicholson has considered other schemes for locating these troubles. I wonder if he has tried to locate a broken insulator by merely passing the current over the faulty wire to ground and measuring the induced voltage in a neighboring wire—one of the transmission wires, neighboring telephone lines, or anything that happened to be handy. Assuming the wires at uniform separation, the induced voltage should be proportional to the length.

William McClellan: It appears as if every essential point had been considered in the design of Mr. Hewlett's insulator. In the long run it should be cheaper, though the first cost would remain the same as for present types. Those of us who have had experience with large 60,000-volt insulators made of cemented shells know what it means to discard an insulator because of a simple broken shell. Another point is the benefit of the full dielectric strength of the material used. We all know that the breakdown potential of a cemented insulator is considerably less than the sum of the breakdown potentials of the separate shells.

Regarding Mr. Hayes' paper, I think emphasis should be laid on the desirability of the open type of wiring for potentials over, say, 25,000 volts. For higher potentials there is a strong tendency among engineers toward outdoor stations, though it must be acknowledged that the last word on this subject will not be said for some time to come. I think that we should cease putting up ordinary knife-switches to be opened with a pole in the hands of a man on a shaky platform 25 feet from the ground. Very simple switches to be opened from the ground have been designed by certain operators in the West and marked attention should be given to this simple but, at times, very important part of the high-tension apparatus.

W. N. Smith: Has the matter of icicles forming between the successive petticoats of insulators of the type proposed by Mr. Hewlett been given due consideration? It would seem as though a chain of insulators, one above the other, might perhaps enable icicles to be formed that would connect from one disk to another. Unless there has been experience to the contrary, I should hesitate to condemn the ordinary petticoat type on account of icicle formation between petticoats, which I think would be fully as difficult to consummate with the petticoat type as with the new insulator proposed by Mr. Hewlett.

L. C. Nicholson: In regard to Mr. Taylor's suggestion as to measuring voltage generated in a parallel wire, I will say that some such methods have been undertaken, but the results obtained were not encouraging, particularly on account of parallel circuits which were in operation at the time, interfering with any measurements of induced voltage in the parallel wire. In case of only one line, I presume some such test could be made, but having more than one line one interferes with the test on the other by electrostatic and electromagnetic induction. In any case, I think it would be necessary to have two instruments; an ammeter to measure the current flowing, and a voltmeter to measure the induction.

S. Q. Hayes: The 200,000 kw. given as the capacity of the oil circuit-breaker is correct; that is, the manufacturers guarantee that that switch will be able to open any overload or short-circuit that will occur on the station having that capacity on the bus-bars. Up to the present time there is no station with that capacity on the bus-bars.

In connection with the troubles in pulling disconnected-switches, it has been proposed in several cases where the disconnecting switches are in rather inaccessible positions to operate, them by means of a soleloid or motor-driven mechanism.

J. H. Finney (by letter): It seems to me that Mr. Mershon's method of tying-in is not so simple as might be employed, although the tie is very ingenious; the chief objection to it is the large amount of tie-wire required, and the fact that the cable is not firmly fastened to the insulator, but simply lies in the top groove.

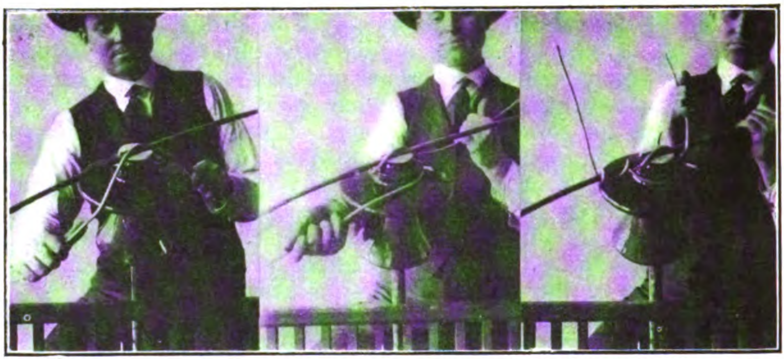

FIG. 1. FIG. 2. FIG 3.

I would like to call attention to a tie which not only embodies simplicity and a small amount of tie-wire, but has the advantage of holding the conductor firmly on every side, as will be seen by the accompanying illustrations. The tie is made by straddling the line wire and top of the insulators as shown in Fig. 1. Both ends are then carried around the neck of the insulator in the same direction as shown in Fig. 2. Having made a half circle of the insulator, the ends are made off by taking a number of turns around the line conductor shown in Fig. 3. This makes a symmetrical tie, the conductor being held without danger of kinks, and is not subjected to any strains which would tend to cause abrasion and breakage of either tie-wire or conductor. The strain is uniformly distributed around the head of the insulator, the conductor being held firmly in the groove. This tie is decidedly cheaper than clamps, is more easily installed, and, in my opinion is not only more desirable than clamps, but is one of the best designed ties, from all standpoints, of which I have knowledge.

F. G. Baum (by letter): When trouble occurs on a line similar to that considered by Mr. Nicholson, the station operator would try to find the section of line on which the trouble is located. The trouble may be a broken insulator, or it may be more serious, and repeatedly to throw power on a disabled line to test it may at some time cause very serious consequences. Furthermore, having located the section of the line in trouble, the operator would at once start patrolmen from each end of the section. After the point at fault is located it will require one man, and very often two men, to repair the break. Until the men arrive at the break it is not certain what must be done and what materials will be required. Hence, while the test method may be of some advantage in some cases, generally one would have to use the sure way in addition to it. Power should not be thrown on a disabled line more than necessary, as life and property may thereby be endangered.

DISCUSSION ON "PROPOSED CODE OF ETHICS", AT NIAGARA FALLS, N. Y., JUNE 28, 1907

(*Subject to final revision for the Transactions.*)

Schuyler S. Wheeler: The report I have to present represents the work during the last year of a special committee of three consisting of Charles P. Steinmetz, Harold W. Buck, and myself. The committee was appointed at the last annual convention to take up questions that were raised by the presidential address of last year on the subject of engineering honor. This address brought up the subject of ethics and the professional conduct of engineers. A committee was appointed to look into the matter and see if any kind of a code should be prepared.

I am happy to say that our committee has been most harmonious in all of its conclusions. We have not disagreed over a single feature in the entire report. Another matter that I want to mention is that we have no idea that the present report is right throughout. We look upon it as a mere starting point, and we think that it will be very useful to us all, because it will at least furnish us what engineers call a datum line; and taking this we can go on with it and make improvements, and constantly make our list of principles better as time goes on.

The report was presented to the Board of Directors and accepted and ordered to be printed and sent to all of the members of the Institute in order that they might examine it so as to pass upon it intelligently at this convention.

William McClellan: I think that all of us at times have found the need of some such code as this. Questions come to us of more or less importance concerning which we should like to know just how other men of our profession would think. I believe that if this proposed code is examined carefully, it will be found that we are not limited or constrained by minor details but are given broad principles which may be interpreted according to the facts of the particular case. No doubt some of us would write such a code differently in details and would, perhaps, desire to have certain changes. This, however, should not prevent it from receiving favorable consideration from every member of the Institute.

Henry G. Stott: I think that the committee has done very admirable work in bringing together for the first time a code of ethics for the American Institute of Electrical Engineers, but there are some individual rules with which I do not agree at all. Take, for example, No. 11, which reads as follows:

> 11. Operating engineers should consider themselves responsible for defects in apparatus or dangerous conditions of operation, should bring the same to the attention of their employers and urge remedial action. If the causes of the danger are not removed they should withdraw.

Now, that is purely academic. Is there in this room any operating engineer who would do a thing like that? I for one would not, because the conditions may be such that it is absolutely impossible for the employer with all the resources at his command to overcome these defects. The operating engineer would not be doing his duty if he should withdraw; his duty is to stand by the apparatus and his employer until such time as the defects can be remedied.

I also take exception to the following rule, No. 12, which states among other things that,

> 12. It should therefore be clearly understood at the outset just what the extent or the limitations of responsibility of the engineer are to be.

Personally, I would not have a man work for me who started out with such a conception of his duties. I would want a man who would agree to accept responsibilities beyond what I ask him to accept at first, and I think every employer would feel the same way. I would not want to have it understood that an engineer is responsible up to that particular bolt or this particular plate and not any further, and the next man who comes along is responsible for what follows. If there is something wrong, is it not our duty, as engineers, to report it ?

I think the rules are altogether too specific, and I would like to see them recast so as to make them broader.

Rule 20, states that designs, data, records, and notes obtained by an engineer employed on salary, are his employers' property; while the same matter in the case of a consulting electrical engineer paid by fee or by commission, are the property of the consulting engineer. I do not see the fine point in that distinction.

Then, again, Rule 26 as follows:

> 26. In giving expert testimony before judicial bodies, the electrical engineer should confine himself to brief and clear statements on engineering or historical facts. He should not give personal opinions without so expressly stating, and should avoid pleading on one side or the other.

The man who is on the stand giving expert testimony does not get a chance to express himself. It is entirely up to the lawyers as to what the man says. He usually says " Yes " or " No ", and he does not get a chance to express his opinion.

Rule 32 provides:

> 32. He should not take a position left by another electrical engineer without satisfying himself that the former has left it voluntarily, or for proper reasons.

That is a perfectly correct attitude, but it may be there would be such a condition as that a man has been ill, or has absented himself from duty for some reason or other, and he cannot be reached. Under these conditions should we say that the employer has not the right to ask some one else to take up his duties if the man has absented himself ? I think not.

H. W. Buck: Mr. Stott thinks that some of the rules are too specific. It was with the full knowledge of the committee that some of the rules were made very specific, and it was the belief of the committee that by only making them so radical and specific could general criticism be brought forth, by attracting attention to the various questions at issue. The committee realizes that many changes will have to be made, but I personally feel that if it is the sentiment of the meeting to have such a code at all, the best way is to recommend its adoption as offered by the committee. If it is allowed to lapse and further criticism is called for by correspondence or vote, I think it will simply result in the gradual disintegration of the proposed code through excessive criticism.

Charles F. Scott: I think that we should accept the report and have it published to the membership, with the strong endorsement it has in the names of the committee; that our Board of Directors should be asked by this meeting to continue a committee of this kind for consideration of suggestions which may be made to the committee and that the committee be asked to present a redraft of the report.

At the beginning of the next session, on Friday morning, June 28, 1907, **President Sheldon** said: The Chair will entertain a motion to the effect that the report of the Code of Ethics Committee be referred to the Board of Directors for their consideration.

[The motion was made by Henry G. Stott, seconded by Lewis B. Stillwell, and adopted by the Convention.]

DISCUSSION ON "CHOKE-COILS VERSUS EXTRA INSULATION OR THE END-WINDINGS OF TRANSFORMERS," "PROTECTION OF THE INTERNAL INSULATION OF A STATIC TRANSFORMER AGAINST HIGH-FREQUENCY STRAINS", AND "NOTES ON TRANSFORMER TESTING", AT NIAGARA FALLS, N. Y., JUNE 26, 1907

(Subject to final revision for the Transactions.)

S. M. Kintner: I have tried to make clear in this paper that, for a given expenditure to safeguard against transformer interruptions caused by line surges, more can be accomplished by the use of choke-coils and transformers with reasonable insulation than by adding extra insulation on the end-turns of the same transformer and omitting the choke-coil. It is not my contention that an inferior insulation can be used when choke-coils are employed and satisfactory service got with such an arrangement. Reasonable insulation on transformers of 1000 kw. and upward should be able to withstand from 5000 to 8000 volts between turns.

A. H. Pikler: At the meeting on December 28, 1906, while discussing the paper of R. P. Jackson on lightning protection, the chairman of the transmission committee said:

> If we must have choke coils, let us put them in the same case as the transformers, and so save the complication in station wiring. Better still, let us do away with them altogether, and put such amount of insulation as may be necessary on the end-turns of the transformers; such amount of insulation as will take care of considerable strain between the end-turns. Then if we use a low-resistance arrester or its equivalent, we shall, I think, have ample protection.

This was the first time I had heard advocated such principles. They must have been considered of particular importance and interest because this very subject is treated in two papers of the present convention. Mr. Kintner recommends the use of a choke-coil within the transformer tank, with no extra insulation on the transformer winding; Mr. Moody recommends the extra heavy insulation of the end-turns, and considers the choke-coil superfluous.

From the points of view of both the designer and the operator or station man, I consider the application of either scheme a retrograde step. In designing we should strive for simplicity in construction. The transformer is a simple and classical piece of standard electromechanical apparatus; to use part of the transformer to perform a duty entirely different from that of transforming and transmitting of electrical energy, viz., the duty of the protective apparaus, endangers the simplicity of transformer construction, and both the transformer and the choke-coil would eventually suffer. This is true whether the choke-coil be within the transformer tank and no extra insulation is used on the transformer coil, or the choke-coil be made an integral part of the transformer by putting extra heavy insulation on its end-turns. From the point of view of the station man, I should expect the protective apparatus to protect the main equipment even at the cost of destruction of the protective apparatus itself.

Therefore I recommend the use of the choke-coil outside of the transformer tank, and also extra insulation on the end-turns of the transformer; but the extra insulated end-turns not at all intended to take the entire duty of the choke-coil. Then if something must break down, it will be the choke-coil outside of the transformer tank. Its cost is only a few per cent. of the cost of the transformer, and the interruption of operation of the power plant will last not more than a few minutes, whereas if the choke-coil is inside the tank, either as a separate piece of apparatus or as an integral part of the transformer, this interruption may last for hours or even days.

We all know that in the case of resonance; that is, when the periodicity of the disturbance, the induction, and capacity coefficient have the following relation:

$$2\pi \sim = \frac{1}{LC}$$

then the phase displacement will have the value

$$\phi = 0$$

and the rush of current will be impeded only by the ohmic resistance

$$I_{max} = \frac{E}{R}$$

and a breakdown follows.

This is what Dr. Steinmetz had in mind when he perpetrated the conundrum: "When is a choke-coil not a choke-coil?"

P. M. Lincoln: I am of the opinion that the choke-coil in connection with high-voltage transmission and high-voltage transformers is a perfectly logical piece of apparatus to use, and the reasons for its use, I believe, are completely, although briefly, set forth in Mr. Kintner's paper and the other papers which deal with the subject. I do not believe we can emphasize too much the value of the choke-coil, owing to the fact of the adjacent turns of the choke-coil having no voltage continually applied between them, as is the case in the transformer. When we come to analyze the matter of putting extra insulation on end-turns of the transformer, we find that it means usually considerably more than is indicated by the paper which was presented by Mr. Moody. Transformers are specified often not only to run upon full voltage, but also to run upon half voltage; also they are frequently specified to be able to run with a delta connection for one high-tension voltage, and a star connection for another; and further, they are often specified to have a range in ratio of 10 or 20 per cent. Therefore, virtually all the taps have to be end taps, with the result that we have to extend that heavy insulation practically from one end to the other. If, therefore, we can take a separate piece of apparatus, such as a choke-coil, and design and install that so that all of these heavy surges which come in can be developed across the turns of the choke-coil, we can thereby save considerable in the transformer and also protect the apparatus to a greater extent.

J. W. Fraser: Looking at this subject from a commercial point of view, I believe that the size of transformers should have something to do with this question. We have on our system, for instance, forty small sub-stations, varying in capacity from 600 kw. to 3000 kw., and will ultimately have a great many more. We practically install four sizes of transformers: 200 kw., 300 kw., 500 kw. and 1000 kw. If we should design each sub-station for large oil-insulated choke-coils, the building would cost considerably more, and the coils would cost nearly as much as a spare transformer. So we have decided to use the coil with large impedance in generating stations where the cost of the transformer warrants it, and comparatively small air-insulated choke-coils, say 20 or 30 turns, in our sub-stations. We make the small choke-coils ourselves at a very small cost. By keeping one or two spare sub-station transformers of each size in stock at some central point of our system we eliminate any chance of a long shutdown.

W. N. Smith: I am disposed to agree with Mr. Kintner in the matter of having separate choke-coils outside the transformer. The tendency toward standardization would naturally incline us toward simplified transformer construction. I look forward to the time when companies operating large transformers will treat them as they do generators, and make their own repairs when they burn out. It frequently happens that when a large transformer burns out, it has either to be sent back to the factory, or an expensive corps of winders has to be sent to the point where it happens to be located. The simpler the transformer coils can be made, the less will be the necessity for such an expensive repair operation. When it is possible for a large power or lighting company with several sizes of transformers to carry in stock a minimum number of standard transformer coils for repairs, economy will result. Viewed from this standpoint, the employment of separate choke-coils will tend toward the standardization of transformers. I also believe it is desirable to have the extra protection of choke-coils for other things than the transformer itself, particularly in a sub-station. Lead-covered cables are extremely sensitive, and as liable to break down as the winding of a transformer, and I believe that the choke-coil is of considerable use as a general protective device in preventing destruction of cables where used in the outside portions of the transmission line, as well as in power houses and sub-stations.

It may be impossible to devise standard choke-coils applicable to all conditions; but as another speaker has said, the power companies are perfectly able to devise them to suit particular conditions.

Another point to consider is the location of the choke-coil in the circuit. That depends to some extent upon the construction of the choke-coil; whether it is mounted on a wooden support or porcelain insulators, or immersed in oil in an iron case. As surges frequently jump across from a transformer or choke-coil to the iron of the containing case, and can thus make destructive short-circuits, the position of the choke-coil in the circuit should be such that there is some protection outside of it in the shape of fuses or circuit-breakers, particularly if it is to be confined in an iron case. While a believer in the choke-coil, I desire to call attention to this problem of so placing it that a possible short-circuit from some part of it will not cause more damage than it is intended to prevent.

Charles W. Stone: One thing not yet considered is that in one instance a long overhead line was carried into a distributing station, and from this station underground for a considerable distance. In this distributing station lightning-arresters with multiplex connections and choke-coils were installed; the idea being to keep any disturbances which took place on the overhead line away from the cable system. It was found that disturbances occurred in the cable system, and on account of the installation of choke-coils were prevented from discharging across the multiplex connections of the lightning-arresters. Therefore in this case it would be better to have eliminated the choke-coils. The other alternative would have been to put in two sets of static dischargers; one on the overhead line, and one on the cable system, which would have added considerably to the expense and complication. Of course if a choke-coil is placed in circuit and is air-insulated and has a comparatively few number of turns, it might be possible that high-voltage disturbances on the cable system would jump across the turns of the choke-coil, and discharge themselves across the multiplex connections of the lightning-arresters, as just explained by Mr. Berg.

E. E. F. Creighton: I have attempted to make laboratory measurements on choke-coils to determine some method by which we could choose their dimensions, and I think we shall have to go back to the fundamentals to find out just what the choke-coil is for. With Mr. Berg and Mr. Stone, I think that the choke-coil is sometimes disadvantageous. The function of the choke-coil is to prevent or to hold back high-pressure high-frequency surges long enough to permit the lightning-arrester to get into operation. Every lightning-arrester in operation to-day has a certain dielectric spark lag; that is to say, after the potential is applied to the lightning-arrester there is a brief interval, a few millionths of a second, before the lightning-arrester begins to discharge and lower the voltage on the system. If there is no choke-coil between the lightning-arrester and the transformer, the end-turns of the transformer receive this high potential strain during the interval that the lightning-arrester is getting into operation. These high-frequency disturbances nearly always come from an external source; consequently the practice has been to place the lightning-arrester on the outside of the choke-coil. If the lightning is internal, the choke-coil is then more or less disadvantageous according to its value in inductance. One solution of that problem is to use a large inductance in a choke-coil and to place lightning-arresters both inside and outside the choke-coil. A laboratory experiment demonstrates these statements.

The disrupted discharge method is used with the following apparatus: two choke-coils representing the two choke-coils in the line, a spark-gap on the outside of the choke-coils, on the side the disturbance is coming from, and another spark-gap on the inside of the choke-coils.

The circuit can be better illustrated by Fig. 1. The outside gap is in the location of the lightning-arrester. Now produce a discharge on the outside; set the outside gap so that it will spark, and the spark at the inside gap is comparatively small and weak. On the other hand, open the outside gap until the potential can no longer bridge the gap, and the potential on the inside gap will rise to such a value as to give a spark more than twice as long as the outside gap. On one test, the outside gap was not sparking with a setting of one inch, and the inside one was sparking with a setting of two and one-half inches.

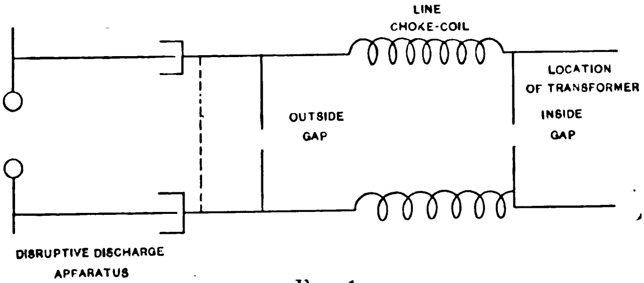

Fig. 1

It seems to me that is sufficient proof, either that this choke-coil should be protected on the inside, or the choke-coil made small enough so as not to magnify the potential on the inside. It is usually a difficult matter to explain just why higher potentials occur on the inside. In this case, of course, the potential came from the outside.

An experience I had last Friday would perhaps be of interest, showing that even with very high values of inductance the transformer cannot be protected from the high potentials. In making some tests on insulators to determine the gap necessary to place on horns in parallel with the insulator to protect it, a condenser was placed across the transformer operating at about

75,000 volts. After three or four strokes, the transformer insulation broke down inside, and on making an examination of it we found it was not the end-turns which were affected, but the third coil down from the end. This transformer is designed to operate at 100,000 volts, and has been used for hundreds of thousands of discharges. We have, however, always used a protective device in connection with it. In the test I refer to it was used without protecting device. In that case you can see there must have been some combination of inductance and capacity giving a resonant condition, which produced high potential very far internally in the transformer. The subject is not simple.

William McClellan: I have advocated external choke-coils and shall continue to do so until there is produced a good low-resistance lightning-arrester with the attributes of an ordinary safety valve; in other words, until the potential at the transformer terminals can be kept practically constant. Extremely low-resistance fuse-arresters work quite well, but they are not self-renewing. Certain types of the horn arrester have given some satisfaction, but they are uncertain. The real question is not so much shall an external choke-coil be used, but shall it be a simple air-insulated coil of a few turns, or an elaborate oil-insulated coil in separate case.

W. S. Lee: As an operating man I am in favor of both choke-coils and extra insulated end-turns. I am continually trying to improve the lightning protective apparatus by putting on first one kind of choke-coil, and then another. Our company is in favor of heavy insulated end-turns and want them on all transformers, for in practical operation, when lightning from the line strikes into the end-turns, we usually find that it goes to the case at entrance to transformer, or burns the terminals off. As Mr. Fraser has told you, we have in the neighborhood of forty stations on our line, grouped about at different places. Some of these stations operate a group of cotton mills who own the station. We have attempted to put protective apparatus at all of these places but it is not easy to get the mill owners to invest in expensive choke coils. However, in our large plants we are installing the choke-coil and getting satisfactory results.

R. P. Jackson: Mr. Moody's statement, that the disturbance is likely to proceed into the tansformer some distance in feet, is, in a way, aproximately true. I think, however, that a better way of measuring the penetration disturbance would be in henrys. Tests I have made indicate that disturbances of the commoner kind will penetrate into the transformer windings, roughly, about 0.04 to 0.06 henrys. A choke-coil of that value put outside the transformer will cause the disturbance to be absorbed or reflected, and very little will go through into the transformer. That value for a choke-coil, 0.04 henrys, is pretty high for a small transformer of low voltage, but insignificant for a high-voltage transformer.

In a paper read by me before the Institute last December, a curve was given indicating that a zero choke-coil would reflect a zero surge, and that the larger the choke-coil the more surge was reflected, with a descending curve something like a logarithmic curve. About 30 per cent. of the disturbance would penetrate through a coil of 0.04 to 0.06 henrys, while very little additional gain was to be obtained by increasing the size of choke-coil. At that point, about 70 per cent. of the surge was reflected, or failed to appear any farther in the windings, so it would seem that if extra insulation were to be put on the proper number of end turns to get safety, we should cover approximately the number of henrys previously given; or 0.04, not considering the iron, which would be a reasonable amount for this extra insulation to be placed upon.

I doubt if any harmful effect from choke-coils occurs very often. The damage to a transformer as the result of switching is usually the result of a sudden change of potential at the terminal of the transformer. Mr. Tobey's paper indicates that the breakdown of the spark-gap at the terminal of the transformer causing a breakdown of the insulation between the turns, is simply a case where the terminal suddenly dropped in potential while the rest of the transformer winding had a comparatively high potential; the result was that the charge on the interior windings attempted to get out at the point of low or zero potential, resulting in a breakdown between turns. A choke-coil at the terminal of a transformer will simply make this change of potential at the terminal more slow in occurring; that is to say, this sudden change occurs at the terminal of the choke-coil instead of at the terminal of the transformer, so that unless the cases are very special—something I have not encountered—the disturbances, whether from the inside or the outside, will be dampened out; their effect on the transformer will be much less if there is a choke-coil of some appreciable inductance than if there be no choke-coils. In other words, the disturbance reaches some distance into the windings from the end or terminal, whether this be the terminal of the transformer, or of the choke-coil.

If the electrolytic lightning-arrester makes good its promise, I think there will be a fair chance of either omitting the choke-coil entirely or making it much lighter, because the electrolytic arrester will be able to keep the potential to a fixed point at the terminals of the transformer.

"When is a choke-coil not a choke-coil?" was, I believe, propounded by Dr. Steinmetz sometime ago. This conundrum has very little bearing on practical matters. If the frequency is so high that, due to condenser effect, it will go through a choke-coil, it will also go on through the transformer for the same reason, and do no damage in either case, so that when one can truthfully say that when a choke-coil is not a choke-coil, there is no need of a choke-coil.

C. P. Steinmetz: The purpose of the choke-coil is to protect the station apparatus against the entrance of high voltage. Therefore, the choke-coil must be between the apparatus to be protected and the source of high voltage, that is, the transmission line as the main source. The choke-coil must therefore be immediately at the transmission line, next to the lightning-arrester. As a good and convenient location for the choke-coil, I recommend the transformer tank. That means, however, that the transformer must be the first piece of apparatus on the transmission line. This is seldom the case. Frequently a number of transformers feed together into high-potential bus-bars and a number of transmission lines are operated from the same bus-bars. In that case, then, we have the transformer switches between the transformer and the high-potential bus-bar, and the feeder switches between the bus-bar and the transmission line. Now, these high-potential bus-bars, the transformer switches, the feeder switches, the current transformers, the connection of the potential transformer —all must connect in between the choke-coil and the transformer; otherwise these different pieces of apparatus are not protected by the choke-coil. This appears to me rather to make the arrangement complicated and impracticable where the choke-coil is desired in the same case with the transformer. Furthermore, we must consider that the choke-coil receives lightning potential; that is, it requires a much more careful installation than the transformer, and the liability to puncture by discharges jumping across surfaces, etc. at the entrance to the choke-coil is much greater than that with any other apparatus and it appears to me the immediate neighborhood of the choke-coil to other apparatus is just as undesirable as that of the lightning-arrester. To avoid this difficulty one very simple way is to have no insulation but air, and it may then be feasible to put a choke-coil out-doors, up on the poles between the transformer station and the lightning-arrester house, where such exists. In those cases where there is other apparatus between the transformer and line, then in addition to the choke-coil which is on the line we require either a second choke-coil at the transformer, or special protection of the transformer, because the transformer also is a source of high potential, as Mr. Thomas showed us some years ago, and we have to guard against that also. The simplest way is the extra insulation on the transformer, which in this instance appears not as alternative to the choke-coil on the line, but as a protection against self-destruction of the transformer, in addition to the protection afforded by the choke-coils against the entrance of high potential from the outside.

The second point I desire to draw attention to is the curious experiment of Professor Creighton, where at the point beyond the choke-coil the voltage of the disturbance was greatly increased. Let us, for instance, consider the transmission of 10,000 kw., at 33,000 volts, 60 cycles, three-phase 33,000; volts between lines means 19,100 volts from line to ground, and 175 amperes per line. Assuming the choke-coil to consume one per cent. of the voltage, that is, a very large choke-coil, as proposed, this gives a reactance:

$$x = \frac{191}{175} = 1.09 \text{ ohms},.$$

hence an inductance:

$$L = \frac{x}{2\,\pi\,N} = 2.88 \text{ mh.}$$

This choke-coil is interposed between the line and the station wiring, which station wiring also has a certain electrostatic capacity, though small it may be. That means you have an inductance in series to a capacity.

Estimating the capacity of the station wiring, that means of the connection from the choke-coil to the transformers over the different switches, circuit-breakers, bus-bars, etc., as equivalent perhaps or of a magnitude of something like 50 feet of wire, that would give you a capacity of about

$$C = 0.0002 \text{ mf.}$$

The frequency or resonance of this combination of capacity and inductance in series would then be:

$$N = \frac{1}{2\,\pi\sqrt{L\,C}} = 200{,}000 \text{ cycles,}$$

approximately. Any disturbance, wave, impulse or oscillation, coming from the transmission line and approaching this combination of choke-coil and station wiring, if of this frequency, or containing a component of this frequency, meets resonance, and the choke-coil generates voltage, raises the voltage in the station to—theoretically—infinity. Well within the range of lightning frequencies is 200,000 cycles; that is, impulses of static induction from the clouds, etc. A large choke-coil even with moderate voltage may build up, due to the inductance of the choke-coil in series to the station capacity, and produce a high voltage, and instead of protecting, the choke-coil so may produce destructive voltages, by resonance with the capacity of the station wiring. That is, a large choke-coil may be a source of danger, and this danger must be kept in view. At much higher frequency, and lower capacity and inductance, this phenomenon was shown experimentally by Professor Creighton: the inductance of the choke-coil in series with the capacity of the connection back of it, raising the voltage of the Leyden jar discharge to the much higher value observed beyond the inductance.

The conclusions to be drawn therefrom are that the length of wiring between the choke-coil and the transformer should be as short as possible, and that the choke-coil should be of as low inductance as possible; that is, as low an inductance as will still give a sufficient decrease of the steepness of the wave-front to allow the lightning-arrester to take up the discharge; but not more than that, because any increase beyond that inductance lowers the frequency of resonance and therefore increases the liability of picking up destructive voltages from line impulses. These two conditions should be very carefully adhered to: the lowest possible static capacity of the circuit between the choke-coils and transformer end of the line, and the lowest possible inductance of the choke-coil which still gives sufficient protection, and with these two limitations I also believe in the desirability of the choke-coil between the overhead line and the station, because it decreases the steepness of the wave-front of the incoming wave, and so acts beneficially.

Ralph D. Mershon: I do not care much for choke-coils, unless they are small enough to be put out of doors. In my opinion, choke-coils inside the station make the station wiring very difficult. If indoor choke-coils are used, they should be inside the transformer case; otherwise, I would rather have the end-turns of the transformers insulated to act as choke-coils. It seems to me there is a good deal of needless objection made to insulation of the end-turns in cases where different voltages must be obtained. Mr. Moody shows how voltage taps can be got without interfering with the end-turns, by varying the number of turns at the middle of the winding, instead of at the ends of the winding. It seems to me that in the case of multiple and series connection, to obtain full or half voltage, a somewhat similar course could be followed, and the same end-turns used for the multiple or series connection. Of course, in such cases, the end-turns will have to be made with a carrying capacity sufficient for the multiple connection. In most cases, I do not think this would be a serious matter.

The depth to which the disturbance penetrates a transformer is a matter of frequency. Until we get further data as to the frequencies which actually occur in practice, it seems to me that we cannot make much headway in determining how far the disturbance penetrates.

In regard to Mr. Tobey's paper. in most cases I have found it very difficult to measure the resistance of large transformers by the fall-of-potential method, because of the difficulty of keeping the direct current perfectly steady. It is not always possible to have a storage-battery for such measurements, and the voltage of a generator driven from commercial circuits generally varies enough to introduce serious errors into the measurement. I would like to know what source of current Mr. Tobey uses in this method of measuring the resistance of transformers in the field.

I judge from Mr. Tobey's paper that he contemplates making the resistance test before the temperature test. It seems to me the resistance test should be made after the temperature test and with the transformer at normal temperature. I gather, also, that he has in mind making the final insulation test before the transformer goes out of the factory. Such practice I do not consider as either proper or safe. A transformer might stand 500,000 volts in the factory; but by the time it has been shipped and installed, it might not be able to stand 5,000. What the customer wants to know is what the transformer will stand after it has been installed and under operating conditions, as regards temperature, etc.

I am rather surprised at the dielectric time-voltage curve given in Mr. Tobey's paper. I had no idea that the dielectric strength of insulation in ordinary use diminished so rapidly or diminished to such an extent as he shows. It would be interesting to know the nature of the insulation on which the curves are made. If the curves are correct, it seems to me that we should have more than a double-potential test of transformers.

If the end-turns of transformers are to be more heavily insulated than the rest of the winding, what is the most satisfactory and intelligent way of specifying such insulation? and what sort of a test can be given the transformer to find out that the end-turns have been insulated in accordance with the specifications?

D. B. Rushmore: In any commercial installation, I think there is no question but that some kind of choke-coil should be installed, and, as a matter of fact, always is installed. The problem is, what kind of choke-coil should be used and what amount of reactance should it have.

The choke-coil is of use in preventing the entrance into the station of current from a lightning disturbance on the line. A lightning disturbance usually takes place during a rain storm when the insulators are wet and break down at the lowest point. The transformers are usually insulated to withstand twice the operating voltage. They will withstand that, and as a matter of fact a great many high-potential transformers will withstand three and a half times normal operating voltage before rupture takes place. If any disturbance occurs on a transmission line, it need only be reduced very slightly in order to protect the transformer, if it has not gone over the insulators.

Lightning disturbances are of a very high frequency, as shown by the short distance which they travel before they break over insulators when the voltage is sufficiently high. The suggestion has been made to protect a station by using fine wires leading into the station, wires of such diameter that an increase of voltage of 75 to 100% above the normal operating value will be above the corona effect on the wires, and thus the automatic disturbance will be largely dissipated outside the power station.

W. LeRoy Emmet: In these high potential disturbances operating through inductive circuits, the danger lies in a condition of elasticity. All of these highly insulated circuits are electrically in a perfectly elastic condition. There is no energy dissipation, and consequently, inductance combining with capacity produces a condition equivalent to that of an efficient spring. If these circuits could be made inelastic, they would absorb such vibrations as Mr. Steinmetz describes. With very high frequencies, small capacities, small inductance may create very high local voltages. It occurs to me that in Mr. Moody's arrangement of insulated turns on the transformer, the practical efficacy may lie somewhat in the fact that the insulation has some power of absorbing energy, and so forms a sort of gradient of potential that penetrates the transformer; whereas with a device like a separate choke-coil, incapable of absorbing any energy itself, that gradient does not exist, and a point of high potential may occur beyond the choke-coil. I had one experience which was perfectly definite, where a choke-coil inserted between a line and apparatus, caused repeatedly the puncture of the apparatus and the failure of the lightning-arrester. It was in a certain case where lightning always came the same way and acted the same way on the circuit. When that choke-coil was put in, the lightning made trouble, and when the choke-coil was out, the lightning made no trouble. In such a case we have a vibrating system with conditions very difficult to predict. If we could have inside the choke-coil or somewhere near the terminal of the transformer some means of dissipating energy, something that would absorb the impulses of high period and voltage, it would kill the resonance, and it seems possible that the leakage and dielectric hysteresis in the insulation may do this; local absorption of energy in the iron may also effect the condition. The electrolytic lightning-arrester should be applicable. It seems to me that some effort in these directions might be expected to give good results.

O. S. Lyford, Jr.: There is one important feature of the choke-coil proposition which I have not heard discussed since I came into the meeting. In his list of objections to choke-coils as now used, Mr. Kintner omitted an important objection to a coil of high reactance immersed in oil; namely, the use of additional high-tension terminals carried out through a grounded case. In a high-voltage transformer station equipped with oil circuit-breakers and choke-coils we now have seven or eight such high-tension terminals per phase; two, or possibly three, for the main transformer, one for the series transformer, two for the choke-coil, and two for the circuit-breaker. Insulation failures occur most frequently in the bushings around such terminals, and it is therefore very desirable to minimize the number of such terminals. Putting the choke-coil inside the transformer case, as proposed by Mr. Kintner, is a step in this direction and also takes care of the point which Dr. Steinmetz raised, that the choke-coil should be as near the transformer winding as possible, but it leaves us still in a dilemma, as we have not afforded to the circuit-breaker and series transformer such protection as the choke-coil gives to these devices. Mr. Kintner claims that a choke-coil affords a fixed amount of protection to any apparatus placed back of it and to obtain this protection we desire to place the choke-coil between the line and all other apparatus.

One logical way to take advantage of Mr. Kintner's suggestion and at the same time minimize the number of high-tension terminals and put the maximum amount of equipment back of the choke-coil, is to put the whole outfit, choke-coil, circuit-breaker, series transformer, and main transformer, all in one tank. There would then be only two, or possibly three, high-tension terminals per phase, and all the apparatus except these terminals would be protected by the choke-coil. I believe this is a practicable arrangement and I recommend it for your consideration.

H. W. Buck: This discussion for and against choke-coils sounds a good deal like a conference on the subject of church unity. Every man is setting forth certain dogmatic beliefs which he has for or against choke-coils. One man may have had a certain experience under a certain combination of circumstances with a choke-coil, which has led to the destruction of his apparatus, and for all time thereafter he condemns choke-coils. The next man has had very good success during certain seasons with similar appliances, while he had choke-coils on his system, and for that reason he is equally certain that the smooth operation of the system has been because of the choke-coils. Both conclusions are probably without any ground whatever. The circumstances which lead to surges of potential which bring destructive results to electrical apparatus have an infinite number of combinations: they depend upon the length of the circuit, the number of sub-stations, the size of the transformers, the transmission frequency, the particular character of the country where the lightning stroke took place, the voltage of the line, the conditions of operation at the moment, the load on the line, the question whether any circuit-breakers went out at the moment or not, etc. Under these conditions, in my opinion, it is absolutely impossible to calculate the problem beforehand mathematically, and equally impossible to demonstrate it experimentally. General conclusions can be figured under a given set of circumstances mathematically; or the transmission system can be set for a certain set of conditions, experiments made, and conclusions reached, but as to whether a choke-coil can be condemned as a universally useless piece of apparatus or praised as an apparatus which cures all lightning or surge troubles cannot be decided at the present moment, and in my opinion can never be conclusively decided.

S. M. Kintner: Mr. Pikler apparently misunderstood me when he took the stand that I recommended the use of choke-coils inside the transformer case. I did not offer that as a recommendation, but merely as a suggestion of a means by which some objections made to the use of choke-coils might be overcome.

Professor Creighton has shown the results of an experiment in a diagram upon the board, and quite general conclusions have been drawn from it. I would like to show by a sketch an experiment I made, and state the results obtained. The experiment was quite simple. This was also a laboratory experiment. I arranged the apparatus as shown in the following sketch, Fig. 2.

In this diagram it will be seen that a static machine (Holtz or one of that type) supplies a charge to an insulated sheet of tin which represents a cloud. Directly below this sheet is another, also insulated from earth, which represents the capacity of a transmission line both to earth and to the cloud. The imitation transmission line leads into a metal box which can be considered as representing the power-house building, or even the transformer-case which is always of metal and grounded. Gap A represents the lightning-arresters, while inductance coil *L*, condenser *C*, are representative of the transformer. Spark-gap *B* is a measuring gap and is used in determining the momentary voltage maximums to which the transformer windings may be subjected in strains to ground when charged clouds in the vicinity of the power-house were discharging.

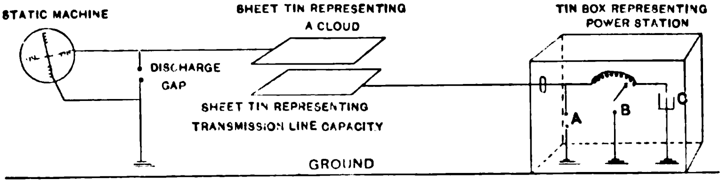
STATIC MACHINE
SHEET TIN REPRESENTING A CLOUD
TIN BOX REPRESENTING POWER STATION
DISCHARGE GAP
SHEET TIN REPRESENTING TRANSMISSION LINE CAPACITY
A
B
C
GROUND

FIG. 2

In brief, the results of the tests showed that gap *B* never discharged when it was larger than gap *A*, and the general conclusion drawn was that a transformer protected by a lightning-arrester would not be subjected to shocks, due to bound charges inside the transformer when they were released by a cloud discharge in the immediate neighborhood, that were in excess of the voltage setting of the lightning-arrester.

W. S. Moody: Of course the purchaser can specify the amount of insulation, or the test that it should be capable of withstanding, but it is hardly practicable to make tests to check this in the finished apparatus. I think the best that can be done in the way of testing is to make up a sample coil with insulation identical to that which will be used in the transformer, and then test the sample. I believe that if we use insulation between layers which will withstand something like 25 per cent. of the line voltage for the outer portion of the winding, we will have a very safe design. Theoretically, a uniformly tapered insulation should be used, but practically, it is out of the question to make more than two or three steps in the amount used. We start with an insulation between adjacent turns or layers that will stand 25 per cent. of the line voltage, and taper this in two or three steps to the normal insulation at a point, say 200 feet, within the winding.

Ralph D. Mershon: To what percentage of the total winding would you give the heavier insulation?

W. S. Moody: I do not think that we can attempt to determine this with any great accuracy. In most transformers 200 ft. should give a length which would absorb any voltage which a good lightning-arrester will not discharge if the voltage is really what is commonly known as high frequency.

H. W. Tobey (remarks made before reading the paper): In the preparation of this paper, the idea was to describe in general some of the more important features of up-to-date transformer testing and also to outline a few of the methods which have been proposed and for one reason or another have been discarded. (Mr. Tobey read the paper, and then replied as follows to various questions):

We find we have usually obtained better results by using a storage-battery for the source of direct-current supply than by using an exciter. If an exciter is used, it is usually found desirable to place in series with it and the resistance to be measured, an auxiliary resistance of such value that the exciter may be operated at approximately normal voltage. Under these conditions, there is ordinarily but trouble due to unsteady voltage. We have felt, as I said in the paper, that it was rather better to make the high-potential test before the heat run, so that in case the insulation was injured by the latter test, the fact would become known during the heat run. There is no other reason, however, why the order of the tests could not be changed if thought desirable.

As to the curve referred to in the latter part of the paper, I may say that it was based on tests made on paper insulation and was purposely selected because it showed a marked difference in dielectric strength between the short time test and the long continued test. The difference is more marked in this curve than we find in ordinary insulation. Usually the change is perhaps 30 per cent.; that is, the dielectric strength would be 30 per cent. less in continued operation than when subjected to an instantaneous test. Attention should also be called to the fact that the sample in question consisted of one thickness only, whereas ordinarily in transformer construction the insulation is made up from a number of laminations so that the factor of safety is well on the safe side.

E. J. Berg (by letter): To me it would seem that relatively small reactive coils and reinforced insulation of the end-turns affords the best protection.

The breakwater analogy used in Mr. Kintner's paper is perhaps as close as any mechanical comparison could be, but it must be remembered that waves are set up on each side of the breakwater and that the apparatus to be protected is located on one side thereof. Consequently, whereas the breakwater affords a good protection for a wave coming from the outside it is objectionable for waves coming from the inside.

Briefly, since not only the line, but electrical apparatus connected to the line under certain conditions that are brought to a very high potential above ground and are suddenly discharged through the lightning-arresters, it is obvious that whereas the reactive coil between the apparatus and the lightning-arrester will afford a protection from the surge which comes from the line, it would be detrimental for the surge which comes from the apparatus itself.

Unfortunately, the inductance and capacity of the electrical apparatus is very small compared with that of the line, or a reasonable section thereof, therefore the frequency of discharge of the apparatus is much greater than the frequency of the discharge of the line. A reactive-coil which has a considerable reactance for the line frequency has an enormous reactance for the surge from the apparatus and therefore may prevent its reaching the lightning-arrester, and may even intensify the voltage.

A practical demonstration of this action of reactive-coils was found some years ago in a commercial installation where reactive-coils of rather high inductance were installed between the lightning-arresters and the apparatus. Upon inspecting these coils after some lightning storms, it was found that discharges had taken place between the inside lead of the coil and ground, discharges representing very considerable voltages. In view of this and the reasons given above, it has seemed best to the writer to use air-insulated coils, which, to be sure, have relatively small reactance, but which are self healing; for excessive voltages they act as an additional number of gaps. The discharge from the transformer being able to reach the lightning-arrester over the turns instead of through them, obviously, insulated reactive coil would not answer in this case.

B. C. Shipman (by letter): The reasons for using a separate choke-coil, as given by the author, far exceed the reasons against it, both in number and force, I think the matter is generally so regarded. To depend on the insulation of the end-turns only, for protection, is hazardous. Even if trouble is escaped in nine cases, the tenth may cause very disastrous results, far outweighing any disadvantages of an additional piece of apparatus, or complexity in wiring. If it be granted that the choke-coil performs the service expected of it, it seems to me to be better engineering to hold up excessive surges and potential strains outside of a transformer, rather than to admit them and then attempt to withstand them by extra insulation. Injury to a choke-coil is comparatively unimportant; to the transformer it is serious.

The reactance of the turns of the transformer-coils themselves will vary according as the transformer is open-circuited on the secondary or not; if not open-circuited, with the load connected. In the latter case, the reactive effect of the primary being less, the extra insulation would have to extend farther into the coil than if the secondary were open-circuited. I recall one instance where three 2000-kw. transformers were connected to the transmission line, but only two were supplying current from the secondaries, the third being open-circuited. A lightning disturbance entered the station, and, passing the protective devices, broke down the insulation between turns of the idle transformer, while it left the working transformers uninjured. This I attributed to the greater choking effect of the idle transformer, causing a steeper gradient of voltage in its coils.

Regarding the advisability of putting the choke-coils in the same case with the transformer, it might be desirable in certain instances for special reasons, but in general I think it would be bad practice. There are enough complications now in a high-tension, multi-tapped, water-cooled transformer, and the interior is hard enough to get at without making it more so.

I agree with Mr. Moody on the desirability of reinforcing the end-turns of transformers, not, however, to take the full force of the extra strains, but to be able to withstand whatever portion of such strains that passes the choke-coils.

Frank G. Baum (by letter): It has been my experience that trouble due to lightning rapidly disappears as the insulation of line and apparatus improves, and when the insulation becomes what it seems it should be, the lightning trouble practically disappears. That lightning trouble is largely a matter of insulation is proved by the fact that, where 15,000- 25,000-, and 60,000-volt lines all pass through the same country, the trouble generally appears on the lower voltage lines. I doubt very much if a first-class insulator will be punctured even by a lightning bolt striking the tower, because it would seem to be very much easier for the lightning to go to the structure direct.

In the protection of a line against lightning in the section of the country where very severe lightning is prevalent, it is not a question of one method versus another, but all the precaution that can be taken at reasonable expense. In some sections extra insulation could be used, on the transformers, choke-coils externally, lightning-rods or ground-wires on certain sections of the line, also horn gaps at certain places to protect against high surges, these horn gaps probably having some resistance connected to ground. It is quite certain, however, that on a high-voltage, high-power transmission system the ordinary spark-gap arresters are useless.

A. C. Pratt (by letter): I believe thoroughly in the desirability of providing extra insulation on the outer turns of a static transformer and placing the taps for voltage adjustment near the middle of the windings. I advocated this method in 1904 in discussion of a paper by Mr. Moody and brought out the further advantage that in case the transformer is operated with less than the total high-tension winding in service, the maximum pressure to ground from the outer turns of the winding is normally never more than that from line wire to ground, which is not the case if the taps are next the outer terminals of the winding.

After eight years' experience and observation on lines operating at from 10,000 volts to 60,000 volts, I am in favor of separate choke-coils in all ordinary cases, and for substantially the same reasons as set forth by Mr. Kintner; I would however favor somewhat heavier insulation between the outer turns of the transformer than between the inner turns, as the outer turns are doubtless often subjected to quite severe strains due to switching and to the inability of the choke-coil to afford complete protection under all conditions. There seems to be no doubt as to the ability of the choke-coil to afford a very large degree of protection.

James Lyman (by letter): The resistance offered to a line disturbance depends directly upon frequency. The frequency of a surge, whether from a short-circuit, ground, or lightning discharge, may be anything from the normal frequency of the line current to a million cycles per second. If the frequency is low, as is the case with many induced lightning charges, the choke-coil offers practically no resistance. Therefore, the transformer windings should be insulated to stand such strains as will not readily be discharged over the lightning and static arrester. A form of choke-coil consisting of 20 to 50 feet of solid copper conductor wound on mandrels 5 or 6 in. in diameter with 0.25 in. air clearance between turns, takes practically no extra room and offers considerable resistance to high-frequency discharges. Extra insulation to the outside turns in high-tension transformer-coils is also recommended as an additional protection against abnormal voltage caused by high-frequency disturbances. The added insulation does not materially increase the size of the transformer, but taken together with the small choke-coils and lightning and static arresters of a reliable design give the most satisfactory results. Where choke-coils of 400 ft. of conductor have been installed between the lightning-arrester and transformers, instances of discharge across the transformer-coils have occurred, indicating a rise in voltage due to the reactance of the choke-coil in preventing the discharge of the transformer. It is my opinion, therefore, that large choke-coils are not always a protection, and, considering other objections to them, they should not be used.

Farley Osgood (by letter): I think it is better to keep the insulation of the transformer as nearly the same throughout as possible, as it saves expense and saves space in the transformer case. I can see no reason for insulating the choke-coil unless it is to be placed in a position where there is insufficient room to carry bare copper, and, generally speaking, the position would not be a good one for any high-tension equipment. If the choke-coil is made without insulation, its perfect condition or damaged state can be quickly and clearly seen, which might not be the case with an insulated coil.

The proper position for choke-coils is in the high-tension chamber, where there should be sufficient room as to make the matter of this slight additional equipment, which virtually requires no attention, of very little consequence from a complication standpoint.

My experience has been that choke-coils are a real benefit on voltages of 33,000 or greater, and, therefore, the use of the coil is recommended in all cases.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 26, 1907.

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(*Subject to final revision for the Transactions.*)

NOTES ON RESISTANCE OF GAS-PIPE GROUNDS

BY J. L. R. HAYDEN

Earth connections in electric circuits are frequently made by driving a gas pipe into the ground. Such grounds are of fairly high resistance, and therefore not permissible where a low resistance ground is required. Their great simplicity and cheapness makes them desirable, where very low ground resistance is not necessary, as for discharging static charges, earthing overhead ground-wires, etc. To get data on the resistance offered by such gas pipe grounds, their permanence, and the variation of the resistance with the seasons, an investigation was started two years ago.

Three gas pipes of 2.5 in. diameter were driven into the ground at distances of 15.75 ft. between I and II, and 7.4 ft. between II and III, in the lawn adjacent to Dr. Steinmetz's laboratory. The soil is a clay loam, overlaying shale rock a few feet below the surface. The pipes are driven into the following depth:

I. 3.75 ft.
II. 2.75 "
III. 3.10 "

The resistance of the three grounds was measured with an alternating 60-cycle current of 120 volts, and as return ground was used the system of the city water pipes. This return ground showed to be less than 0.01 ohms. It was therefore neglected.

Readings were taken at irregular intervals from August 1905 to August 1906, and daily from September 1, 1906 to date: during fall and spring, morning and evening readings were taken to see whether the daily temperature variation had any effects. These however, were found so small that in the attached curves the daily average has been used.

Fig. 1 shows the variation of the three ground resistances during the whole period, and Figs. 2 and 3 the variation from September 1906 to date, in larger scale, so as to show the daily values. The values are given in amperes at 120 volts 60 cycles, and so are proportional to the conductivity.

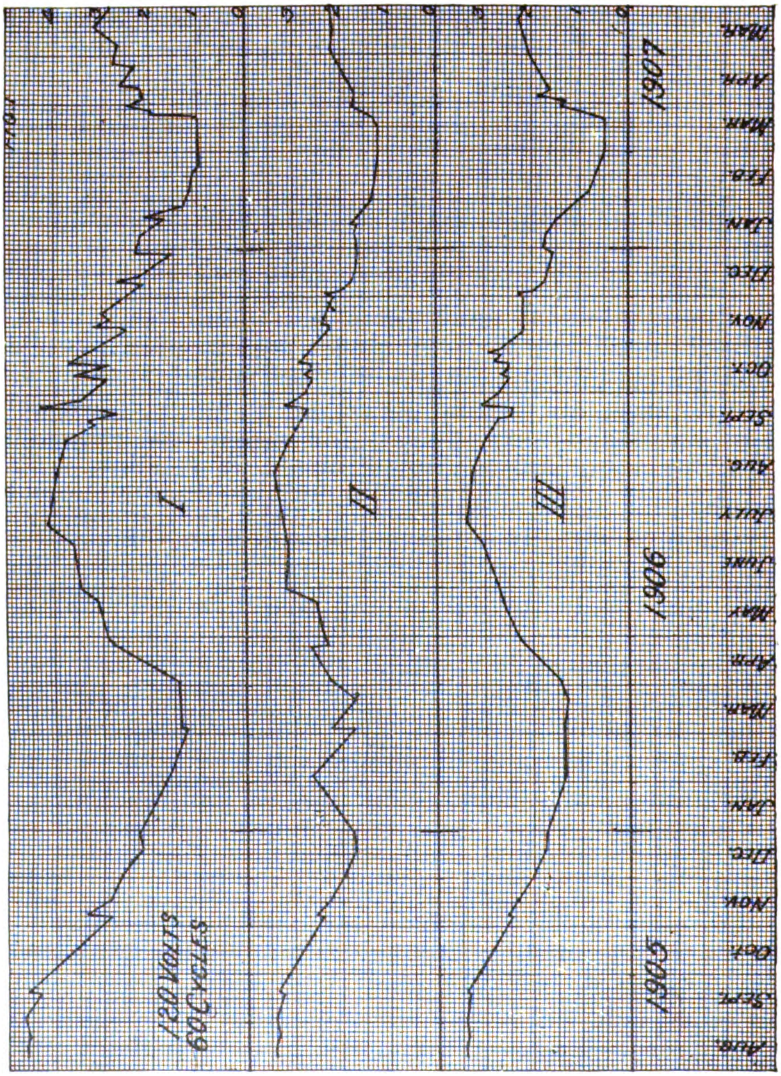

FIG. 1

The lower curve gives the daily average of temperature, and the rain fall, the height of the black line giving approximately the intensity of the rain fall.

The curves show very plainly the sudden rise of conductivity

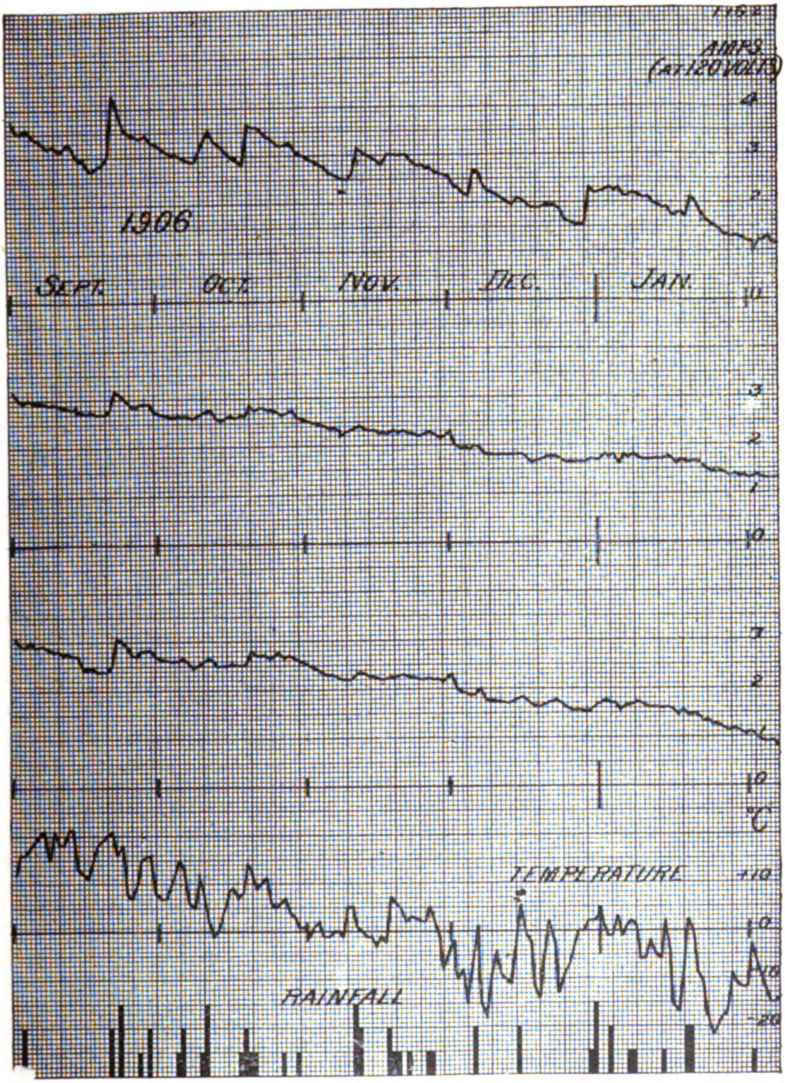

FIG. 2

at rain fall, and the gradual decrease during the following dry period. The maximum of conductivity occurs in July and August. This was rather unexpected, since the wet season is in spring. It seems that the increase of conductivity of the moisture at high summer temperature amounts to more than the increase of moisture during the wet but cooler spring season.

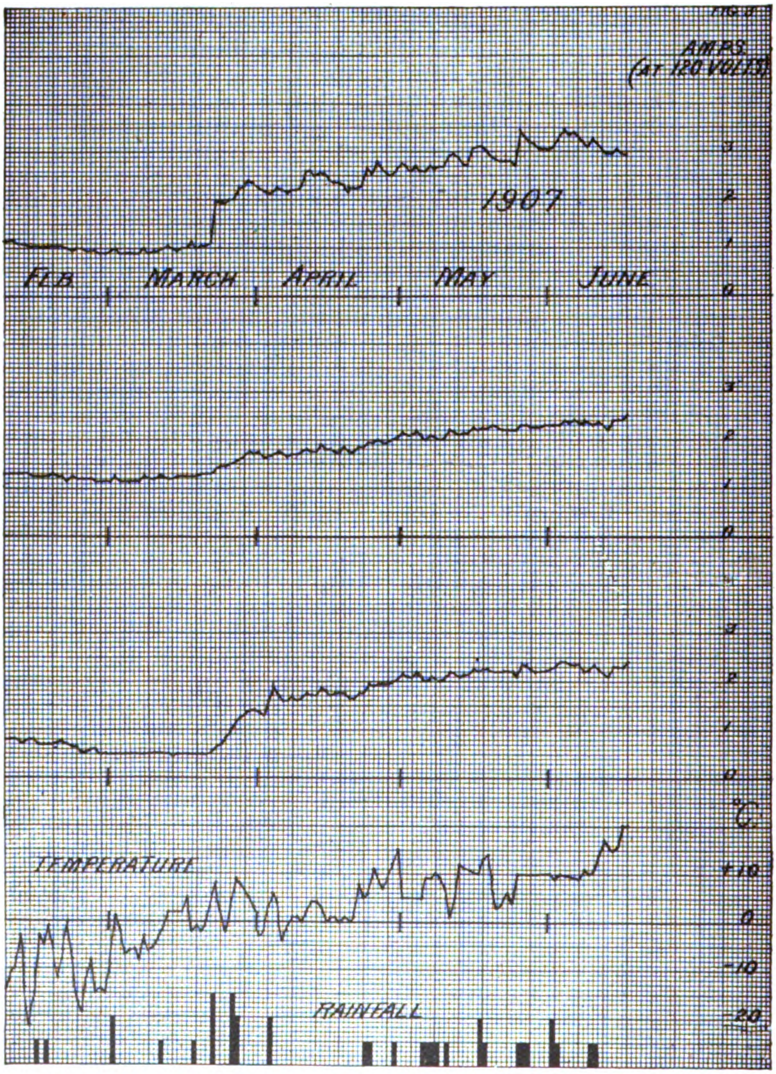

FIG. 3

The minimum of conductivity is towards the end of March. Since thunder storms occasionally occur before this period, this feature requires serious consideration. So far the values of the present year approximately repeat last year's record, except in winter: during the last winter the conductivity decreased to very much lower values than in the previous winter. Whether this was due to the greater severity of the last winter, must remain for further investigation.

Interesting is the great difference between the three grounds although closely adjacent to another. Ground I shows the effect of rain fall and dry periods very much more than II and III. II and III during summer are very closely the same, while I has a considerably higher conductivity, about 30%. From October onward the conductivity goes down, and towards the end of December, II and III, which until then were very closely alike, begin to differ; III decreasing much more rapidly, to a minimum in March, of less than 0.5 amperes or less than one-sixth of the summer value, while II reaches a minimum of 1.15 amperes or about one-third of the summer value, and I, which has been of higher conductivity during summer, falls below II towards the end of January, reaching a minimum of 0.9 amperes. Towards the end of March all three grounds rapidly rise in conductivity, with the spring thaw, in the beginning of April II and III are again alike, and I of higher conductivity than the other two.

It seems herefrom that such gas-pipe grounds are permanent at least for some years, but show a marked annual variation, the conductivity greatly decreasing during winter. But, against expectations, even at the winter minimum, a very appreciable conductivity is left. The most important conclusion is, however, that such grounds show very great individual difference in their annual variation, even when closely adjacent to each other. This matter requires a further and more extended investigation, which has been started and will be reported upon at a future time.

An interesting and useful feature observed was that by the passage of an alternating current through the pipe into the ground, the conductivity gradually increased, for instance:

Circuit closed at noon:

0	hours	after:	3.40	amperes at 120 volts
7	"	"	3.90	"
9	"	"	4.33	"
22	"	"	4.42	"
43	"	"	4.50	"
52	"	"	4.69	"
75	"	"	4.78	"
103	"	"	4.74	"
120	"	"	4.73	"

Circuit opened at noon:

0 hours after:	4.73 amperes	at 120 volts.
7 " "	4.02	"
23 " "	3.62	"

APPENDIX

As the daily measurements of the gas-pipe grounds have been continued during the time which has elapsed since the reading of the above paper, in Fig. 4, the record of Fig. 1 is continued to the middle of February 1908. As seen, the curves in Fig. 4 show the same characteristics and the same values as in Fig. 1:

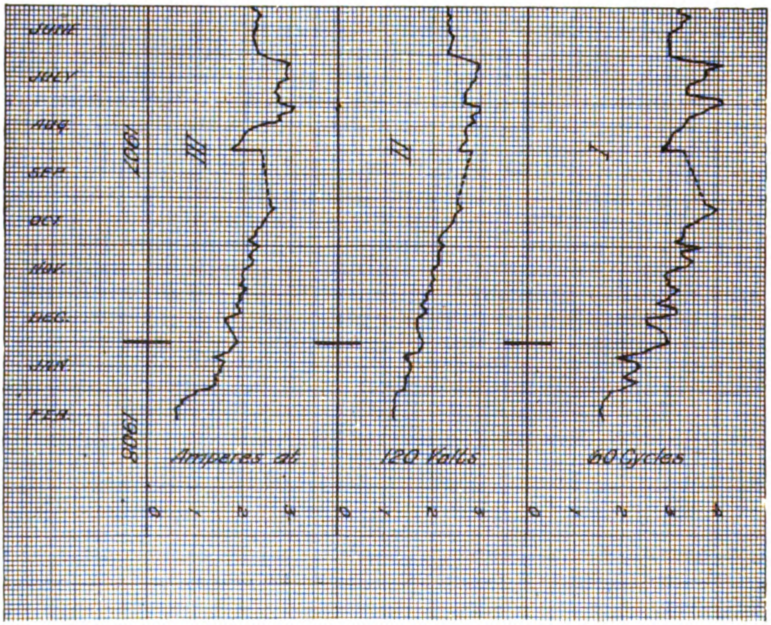

FIG. 4

I gives a higher summer maximum, and a far greater variation of the conductance with the rainfall; II and III are practically alike until the arrival of very cold weather, which this year occurred at the end of January, when III went far down below II in conductance, just as it did in former years.

It seems, herefrom, that at least during the period of observation, of nearly three years, the gas-pipe grounds showed no permanent change, but merely periodic variations with the seasons of the year.

DISCUSSION ON "NOTES ON RESISTANCE OF GAS-PIPE GROUNDS" AT NIAGARA FALLS, N. Y., JUNE 26, 1907

(*Subject to final revision for the Transactions.*)

Chas. P. Steinmetz: It seems that the continuous passage of an alternating current through such a gas pipe to the ground increases the conductivity. This test of increase of conductivity was made in the summer time. It stands to reason that during winter the increase will be very much more because of the melting ice. The curves given in the paper show interestingly how towards the winter the conductivity gradually falls and reaches the minimum towards the end of March and then very suddenly jumps up. It also shows many times after a rainfall a sudden rise of current which gradually fades out, and how all three grounds go together until the end of the year and then the one current becomes very small, while the other is still high, and the low resistance ground has reached a higher resistance than one of the high resistance grounds.

This is only a preliminary report, but it is interesting to know that such a gas-pipe ground, which has been called bad names for a long time, seems to remain a ground even in winter when everything is frozen, even if it does not come below the frost line. It is naturally not good enough to discharge a large current, but is good enough to dissipate all electrostatic discharges which may accumulate in the line. It remains to be investigated whether grounds in different places, different soils, etc. may not give still greater values and show different results.

Ralph D. Mershon: Why not extend these investigations to other forms of ground? Why not compare pipes with some of the other forms of ground.

Chas. P. Steinmetz: That is what Mr. Hayden is arranging to do, to start an investigation on a larger scale. There have been a number of suggestions already made, in connection with gas-pipe grounds, of filling the hole up with coke and salt and other materials. It remains to be investigated, whether there is any benefit in digging a hole and filling it with coke, or whether driving a pipe into the ground is not nearly as good. Another question is as to how the character of the surroundings affect the ground, whether to drive the ground pipe in the middle of a road, or to drive it under trees. We are putting down a large number of these gas pipes scattered over the college grounds at Schenectady, and expect to get further results from these tests.

F. B. H. Paine: Do I understand that the gas pipe introduced farthest into the earth has the least resistance?

Chas. P. Steinmetz: The least resistance, or highest conductivity in summer, but in winter it falls in conductivity below the one which was less deep. The shallowest one showed the best conductivity in winter, more than twice the conductivity of the other one, which was a little deeper, and nearly twice the conductivity of the one which was deepest. We measured at lower voltages by putting high resistance in series; instead of 120 volts, 40 or 50 volts gave the same resistance.

P. H. Thomas: If you had 100 amperes it might be different?

Chas. P. Steinmetz: The resistance would probably go down, due to the heating, and so it would show the time effect. Perhaps with high voltages and extremely large currents, but with a range of 120 volts or less, the resistance would be constant.

Ralph D. Mershon: We made a somewhat similar investigation. The railway companies were very particular about having our structures grounded near the tracks, and they designed some elaborate grounds, groups of steel rails surrounded with coke. Mr. Nicholson made some measurements on the concrete tower foundations and also the resistance of some of these grounds. First he tried to use a Wheatstone bridge, but the stray currents from different places in the country bothered him. Then he used a modified Wheatstone arrangement in which you make use of the stray current to measure the resistance. He got results which were concordant, but he found that with a voltmeter he could always get a voltage sometimes in one direction and sometimes in the other, between the tower and a pipe driven in the ground. Then he drove two exactly similar pipes in the ground, to the same depth, and got a voltage between them. Then he put two pipes in a barrel of water and got a voltage between, and he found he could reverse the voltage by the amount of immersion of the pipe.

F. B. H. Paine: It is my recollection that the same foundation resistances were measured at different times in the year, but certainly during the summer and fall, but I think later on in the winter the variation in resistance was so slight as to be comparatively negligible: it varied between 7 and 10, and 7 and 12 ohms, at different times of the year, the same foundation, not more than that.

N. J. Neall: What is the ohmic resistance of the concrete foundations under the tower?

Ralph D. Mershon: The highest is 20 ohms, and the lowest is 3 ohms from the tower to the ground. These values were got by measuring the resistance between the two adjacent towers and assuming that half the resistance was in each one. I think there is room for further investigation in regard to these grounds, not only as to the ohmic resistance, but as to the part they play in case of surges.

Chas. P. Steinmetz: We are going to try to measure not only with 60-cycle current, but also with the high frequency current, 100 000 cycles.

Ralph D. Mershon: I got one railway company to allow me to dig a trench and put in a strip of copper—they finally agreed to let me put in galvanized iron—with some coke around it to make a good contact with the ground.

Chas. P. Steinmetz: Mr. E. J. Berg some years ago proposed to run a shallow ditch along the line and run an underground wire in the ditch and connect that up with the overhead ground wire and use it as an energy dissipating wire, instead of the ground.

DISCUSSION ON "A NEW TYPE OF INSULATOR FOR HIGH-TENSION TRANSMISSION LINES," AND "SOME NEW METHODS IN HIGH-TENSION LINE CONSTRUCTION", AT NIAGARA FALLS, N. Y., JUNE 26, 1907.

(Subject to final revision for the Transactions.)

J. B. Whitehead: Have any tests been made to determine the potential over these insulators when placed in series? Is the actual distribution 25,000 volts per unit?

Ralph D. Mershon: The more I consider Mr. Hewlett's type of insulator the more attractive it is from many different standpoints, but, I should like to know if Mr. Hewlett has constructed any spans, using these insulators, with the idea of finding out just what sort of mechanical oscillations or waves, or swinging can be obtained. It seems to me that there is a possible chance of these spans swinging so as to arc to the tower. There does not seem to be any chance to use a discharge gap in connection with a line. Any arc close to the insulator has a good chance to destroy the whole insulator, whereas if there were a discharge gap, the arc would rise away from the insulator and it could be saved. It would be extremely difficult to install a line using such insulators and more difficult to repair it.

Ralph W. Pope: This appears to be one of the cases where there is a decided improvement in insulators, with some objections due to manufacturing, which may be eliminated as we go along. It is likely that in the course of time, with greater experience with the insulator, these difficulties may be overcome. Is it not the case with most improvements, that in practice the shortcomings are eventually overcome ?

Ralph D. Mershon: For about three years past we have been conducting some high-voltage measurements in Niagara Falls, under all the various conditions we could think of that would approach actual practice. We took a lot of actual loss measurements on insulators of different sizes, dry and wet. I thought that if we assumed a certain thickness of the films on the petticoats of the insulators, and calculated on that assumption the resistance from the neck of the insulator to the pin, perhaps we could get some relationship between the loss over insulators of various sizes. It would not work out. Some of the smaller insulators had less loss than the big insulators. I think that the petticoats become charged and act as a condenser plate with reference to the pin; and the closer they are to the pin the more effectively the condenser acts to increase the loss and make them flash over. We measured the loss from the neck of an insulator to the pin, with a wooden pin and a metal pin. The wooden pin, if dry, gives fine insulation, and at first thought one would think the loss would be lower with the wooden pin than with the iron pin; but it was a great deal higher. This surprised me. I thought it over and finally reached a probable solution, and this solution has been confirmed by another experiment. The way I explained the higher loss is this: the insulator is taking a certain charging current; the pin has a straight ohmic resistance; and the voltage taken by it is in quadrature with the voltage of the supply current. You might increase the I^2R considerably, without decreasing the current going over the pin. We got a wooden curtain pole, and stuck the insulator on that, and took different lengths of pin. After the first trial it was found that the loss continually fell off as the length of the pin increased.

F. B. H. Paine: There are some features of transmission engineering which are not altogether electrical. The people along the line are likely to insist on having a method of supporting the cables which will prevent them from falling to the earth, or so close to the earth as to become a menace to travelers on the highway because of the loss of one or more points of support. If the cable is supported from above, it will necessitate some means to catch the cable in case an insulator fails and the cable is lowered. Is this provided for in this design ?

Chas. P. Steinmetz: In multigap lightning-arresters very great inequalities exist in the potential distribution only when very many spark gaps are connected in series across a high-potential circuit. With four or five or even ten spark gaps in series, the distribution of potential under lightning-arrester conditions is still practically uniform. There is to be considered, regarding this distribution of potential, between the successive insulator discs the fact that it is a function of the voltage and that when voltage is raised to a point approaching the breakdown strength of one element, then the distribution of the potential changes and becomes more uniform. So it may well be, if there are, say, four elements in series, you get across the first element 50 per cent. instead of 25 per cent. of the total voltage at normal impressed voltage. If now you increase the potential, as soon as it approaches the breakdown strength of the first element, brush discharges occur over the surface etc., and to increase the effective capacity of this condenser, and then the potential distribution becomes more uniform and may be nearly uniform, when you reach the united breakdown strength of the whole system, at least where the number of sections is not very large.

DISCUSSION ON "THE TRANSMISSION PLANT OF THE "NIAGARA LOCKPORT, AND ONTARIO POWER COMPANY," at NIAGARA FALLS, NEW YORK, JUNE 26, 1907

(Subject to final revision for the Transactions)

E. J. Berg: You have a telephone circuit in connection with the power lines?

Ralph D. Mershon: We have a separate telephone line on separate poles on our own right of way.

E. J. Berg: The following observations made in Mexico about a year ago have some bearing on this. A 500-volt direct-current temporary station was furnishing power for lighting a number of buildings on the top of a mountain. The station was located in the valley about 500 ft. below. The lines were strung on high-voltage insulators and were about 22 in. apart. A short time before a thunderstorm, static sparks were seen between these lines. At the time, a number of lamps were burning so that the circuit was closed between the lines within 50 ft. of the spark. Furthermore, these same lines were placed within about 2 in. of each other in the building, yet the spark chose to strike 22 in. in air. A lightning-arrester within 50 ft. of the disturbance would apparently not have taken the discharge.

Ralph D. Mershon: We have line structure lightning-arresters about every 2200 ft. Two or three days ago an insulator was smashed on the tower within 550 ft. of one of these lightning-arresters, set for six inches.

J. W. Fraser: It seems to me that the concrete foundations we are using at the present time are very expensive. We are figuring on a new line, and putting in a sort of button about 2 ft. in diameter, of cast iron, and putting it down about 5.5 feet in the ground. Throughout the Carolinas we have fairly solid earth. I see no reason why this foundation should not be as effective, and it does not cost as much as concrete.

Ralph D. Mershon: Mr. Scholes has figured on metallic foundations and anchorages two or three times, and each time the cost of metallic foundation is more than the concrete.

J. W. Fraser: They are using buttons 18 in. in diameter, that weigh 106 lb. in the West. I understand that they are perfectly satisfactory.

F. B. H. Paine: The towers used in the West are in places where they are not subject to sleet or any of the enormous strains our lines are subjected to in this part of the country. It is reasonable to suppose that they can adopt the metallic foundation, as they can use a lighter tower than we can.

Ralph D. Mershon: Under the assumptions made for the towers of the Niagara, Lockport and Ontario Power Co., the resultant of the horizontal and vertical component forces is 15,000 lb. Under test, the towers must stand twice that.

J. W. Fraser: Wouldn't it be as satisfactory to make a lighter tower and use one strong tower every mile?

Ralph D. Mershon: These towers would not stand the condition of breakage of all the cables. Every two miles we have a guyed tower that will stop all breakages that occur; that is, under the conditions of sleet and wind. Mr. Paine can tell you something about sleet on telephone wires.

F. H. B. Paine: A couple of years ago Mr. Hammond V. Hayes was good enough to relieve my mind of the thought that Mr. Mershon had provided too great strength in our lines. He showed me some plaster casts of wires coated with sleet, which had been subject to a wind, according to the United States Weather Bureau, of 100 miles an hour, the sleet and wind occurring at the same time. That was on telephone wire, and the construction came down. The three or four samples I have in mind, which he showed me, were either from western Massachusetts or along the Hudson valley, in that section, and they occurred during the two famous blizzards.

Ralph D. Mershon: No two engineers will agree on the subject of sleet and wind. If an electrical engineer who has not done much in the way of designing framed structures, designs a line in accordance with his ideas of the wind he will encounter, and submits his designs to a bridge engineer, the bridge engineer will probably say that the assumptions and factors of safety are entirely too low. The factors of safety and assumptions for our structures have been criticized for being too low and for being too high, but I believe we are very close to being right.

J. W. Fraser: I do not think it advisable to provide against abnormal conditions.

Ralph D. Mershon: It depends on the amount of power; a small amount of power is not entitled to the amount of insurance that a large amount of power is entitled to. If there is 30,000 h.p. going over a circuit, there is more depending on the 30,000 h.p. than there would be with 5,000 h.p. You are justified in taking more risk in connection with a 5,000 h p. line than you are with a 30,000 h.p. line. The latter serves a much greater territory than the 5,000 h.p. and industries and utilities which in the aggregate amount to a great deal more than in the case of a 5,000 h.p. service.

J. W. Fraser: We decided that the largest amount of power we could carry over one line normally would be about 6,000 kw. Of course that makes a lighter line.

Ralph D. Mershon: Our conductors starting out over the river are larger than they are farther along the line. The cable is 0.9 in. in diameter; add 0.5 in. of ice and it becomes a good size conductor.

In regard to the question of wind pressure, I would confirm something Mr. Buck said this morning in regard to long spans. When we were crossing the Niagara River we had extended over the river a light rope used as a messenger rope. It responded of course to every impulse of the wind. I have observed this rope with the wind blowing pretty hard, and its average position scarcely changed at all, but the positions of different portions of the rope varied over wide ranges. You could see waves running back and forth over it, showing heavy gusts of wind in one place, and gusts of wind of lower velocity somewhere else. The behavior of the rope confirmed the results of the tests made on the Forth bridge, that there is a great difference between maximum and mean wind pressure, and that the maximum average wind pressure on a small area will be much higher than on an extended area.

J. W. Fraser (by letter): Recently we have had a test made on the holding-down power of metallic anchors and the attached curves have been calculated from data obtained. Mr. Mershon says that " The resultant of the horizontal and vertical component stresses is, I think, 13,500 lb." If this is the stress at a point 40 ft. from ground, and the base of tower is 15 ft., each anchor would have to withstand a pull of 18,000 lb. Referring to curve B, two 10-in. channels 2 ft. long, spaced 26 in. on centers, would have to be sunk 6.5 ft. in the ground. The extra cost of these anchors per tower would exceed the cost of ordinary anchors by about $18.00. I take it that Mr. Mershon was referring to the extra strong towers spaced two miles apart, and if I am correct much smaller anchors would be ample for the ordinary towers.

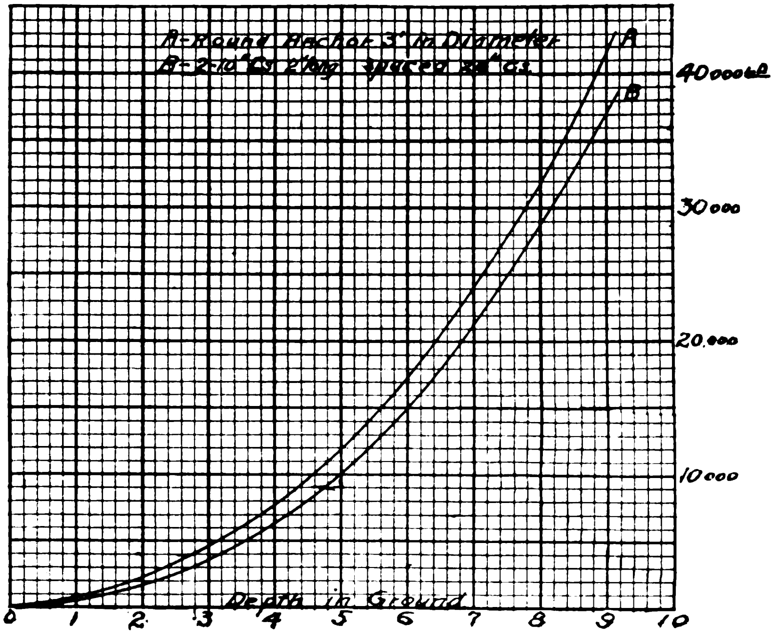

FIG. 1.

It is not only that stone, water, and cement have to be hauled long distances by teams, but the work is delayed excessively, waiting for either the water or the cement or for the foreman to adjust template and set the anchors. In all our line construction we are obliged to provide camping outfits and board for our men, and the delay caused means a great deal more money than the paper estimates of the construction of steel lines.

Discussion on "Location of Broken Insulators and Other Transmission Line Troubles," at Niagara Falls, N. Y. June 26, 1907

(*Subject to final revision for the Transactions.*)

L. T. Robinson: It seems to me that the method proposed is open to some serious limitations, and that the good results obtained are chiefly on account of the experience of the people who have handled it. For instance, in the table, in the first example given, an error of 1% in the determination of either I_1 or I_2 will make the result practically 2,000 ft. instead of 1,000 ft.

Ralph D. Mershon: I understand that this break, 1760 ft. from the station was located in three-quarters of an hour by an ordinary station attendant. One-third of a mile is a small portion of 100 miles.

L. T. Robinson: I was about to say that the thing involved is the determination of the ratio between I_2+I_1 and $I_2—I_1$. It would seem impossible to develop the method further and get much greater accuracy. An instrument could be made having two windings carrying I_2 and I_1 in opposite directions that would measure $I_2—I_1$ directly, and another instrument with two windings carrying I_2 and I_1 in the same direction which would measure I_2+I_1, and these could be combined into one instrument that would determine the ratio of the two quantities directly. This would be an instrument without spring control at all.

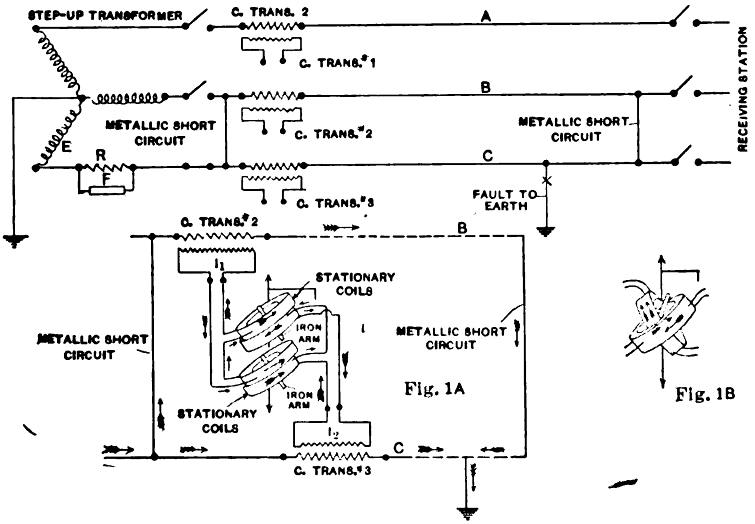

Fig. 1

In Fig. 1 I show such an instrument connected to a circuit **in the same way that the ammeters are connected in Fig. 1, of** the paper. In that part of the sketch lettered Fig. 1A the compound windings are shown acting on two separate iron vanes, mechanically connected, and in 1B both the compound windings act on the same iron vane.

Ralph D. Mershon: You would make these windings affect the same core?

L. T. Robinson: Yes; its action is based on the assumption that the two currents are in phase ordinarily, and that the line resistance, inductance, and capacity are uniformly distributed. An instrument, as described, in which the windings are properly placed, and without spring control, would indicate the ratio between the two values, previously referred to, and its indications could be directly applied to the chart, Fig. 5.

Ralph D. Mershon: These instrument coils would have to be so arranged that they would have comparatively little effect on the circuits that feed them.

L. T. Robinson: The elements of the instruments would be connected to the lines through current transformers, and would have no more effect than any ordinary instrument. Being a ratio instrument, it would simply be the torque that would fluctuate for variations in the currents used, and not the torque ratio. It would be an instrument similar to a power-factor indicator or to a frequency indicator.

F. B. H. Paine: I think Mr. Nicholson has given a good deal of consideration to the various means of improving the details. The purpose of the paper is to indicate the possibility of what can be done with the ordinary commercial things he had about him, and to help us in determining faults and enabling us to correct them quickly. He has not quit thinking about the matter. Mr. Robinson's comments simply reenforce the importance of that.

L. T. Robinson (by letter): To the above I would like to add that since this discussion took place it has been pointed out to me that a much simpler instrument, embodying the same general principles, but in which there are only two simple windings, one carrying I and the other I_2, instead of the two compound windings, referred to above, would be satisfactory. This is obviously true and would simplify the instrument without rendering it less useful.

A paper to be presented at a future meeting of the American Institute of Electrical Engineers.

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(*Subject to final revision for the Transactions.*)

PRIMARY STANDARD OF LIGHT

BY CHARLES P. STEINMETZ

Light is not a physical quantity, but a physiological effect, that of certain wave-lengths of radiation, and therefore can not be expressed in absolute physical units; it must be measured by comparison with an arbitrarily chosen standard of physiological effect. As a result thereof, even with the best existing primary standard of light, the amylacetate lamp, the difficulties of reproduction. and maintenance of its constancy, are such as to involve errors very far beyond those considered permissible in physical measurements. A radical increase in the accuracy of reproduction and maintenance of a primary standard of light appears possible only by relating the standard of light in such manner to physical quantities, that it can be determined by energy measurements.

This led to the recommendation of defining the primary standard of light by the energy of radiation. It requires, however, a definition of the quality of radiation, since the physiological effect of radiation has no direct relation to the energy of radiation: one watt of radiation of a wave-length from the center of the visible range gives a far higher physiological effect, that is, more light, than one watt of a wave-length near the ends of the visible spectrum. This is not merely a function of the quality or color of the light, as light of the same intensity and same color, identical physiologically, may be entirely different physically, and therefore represent a different amount of power. For instance, the physiological effect of white light is produced by the combination of all colors of the spectrum, but also by an infinite number of combinations of two, three, or more spectrum colors; and these physically different forms of white light, while indistinguishable on the photometer screen, and thus physiologically identical, represent different amounts of radiation power per unit of physiological effect, or per candlepower. The same reasoning applies to colored light. The power of the visible radiation is, therefore, not a measure of light.

The definition of the absolute unit of light as the physiological effect of one watt of power of visible radiation, requires, therefore, an arbitrary definition of the distribution of power throughout the visible range. As such distribution of power through the visible range, may be chosen that of the black-body radiation at a definite temperature, and the temperature measurement may be eliminated by specifying the energy-ratio between two definite regions of the spectrum. For instance, such a definition would be:

The unit of light is that given by a black body radiating one watt of power between the wave-length of 39 and 72, under the condition (that is, at the temperature) where the power of radiation from wave length 39 to 55 bears to that from 55 to 72 the ratio a.

It does not appear to me that such a standard would be very satisfactory, and for the following reasons:

1. Though the intensity of radiation at the red end of the spectrum is very high, the physiological effect is very small, and an inaccuracy at this limit would therefore seriously affect the result.

2. The absorption constant of glass or any other envelope is different for different wave-lengths.

3. Any deviation of the radiator from the black-body radiation vitiates the result.

4. The color of the light would not be white, but yellow, due to the temperature limitation imposed by the radiator.

A more satisfactory primary standard of light, based on measurement of radiation power can, as I believe, be produced by selecting three primary colors of the visible spectrum. Let these colors be of definite wave-length, about equidistant from each other, and of such character that they can be absolutely reproduced at high intensity, as the spectrum lines of a luminous gas or vapor. Then define the unit of light as that given by one watt of power radiated at these three wave-lengths, in definite proportions, chosen so as to give white, or yellowish-white, light. That is, the primary unit of light is the physiological effect, as observed on the white photometer screen, of one watt of power, radiated in the three definite wave-lengths A, B, C. in the proportion $a \div b \div c$.

The adoption of this standard of light would eliminate the sources of error which now affect the primary flame-standard. The radiation density or light flux intensity of the three primary colors is measured separately before they are combined on the same photometer screen, and the accuracy of determination would be limited only by that of physical measurement of radiation energy, by bolometer or otherwise.

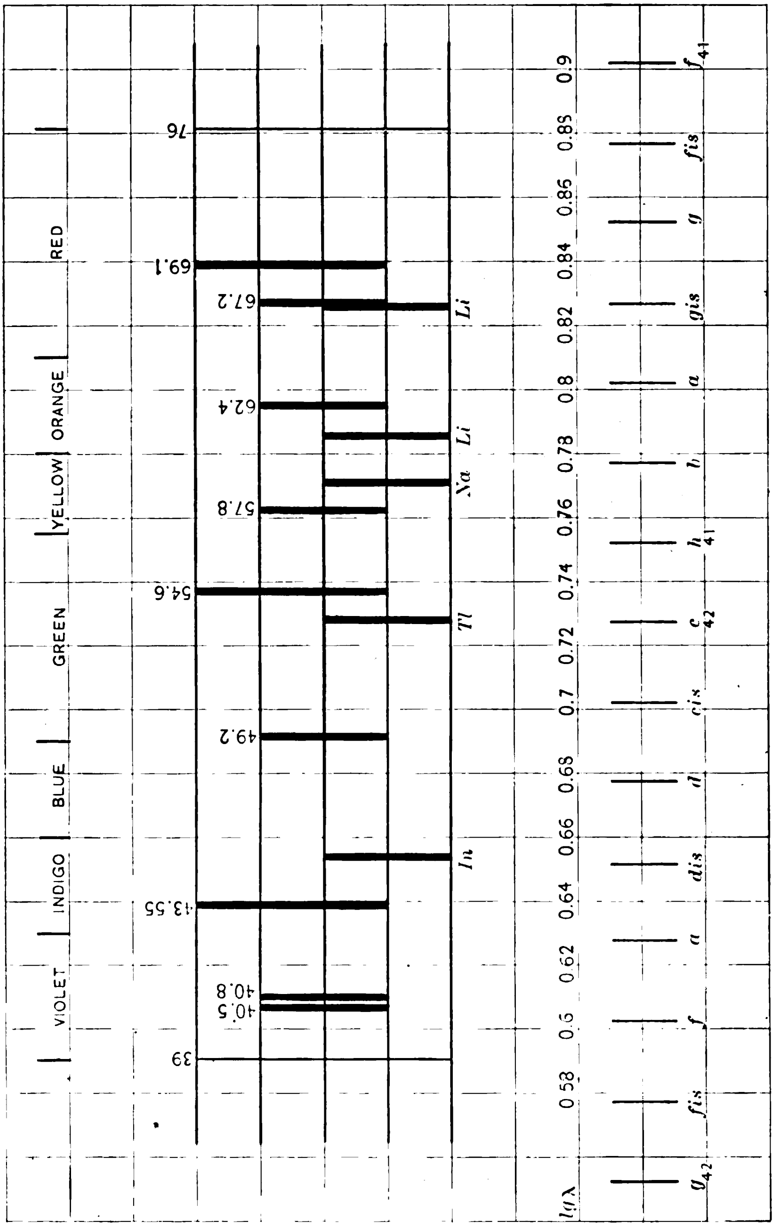
This standard of light requires three sources of monochromatic radiation, which can be maintained constant with any desired exactness. This requirement seems fulfilled by the mercury lamp. When reasonably protected from air drafts, changes of surrounding temperatures, etc., the intensity of radiation of a mercury lamp remains extremely constant at constant current, and, for minor variations of current, varies directly as the current, while that of the incandescent lamp varies as a high power of the current. It must be considered that a reproduction of the same intensity in the lamp is not required, as is the case with standard lamps, since the mercury lamp is merely the source of monochromatic light, and its intensity is measured and adjusted.

I should therefore recommend mercury lamps as the sources of the three monochromatic radiations, which combined give the primary standard of light.

Approximately, some of the brighter lines of the mercury spectrum are shown in Fig. 1 in geometric scale; that is, with the logarithm of wave-length as abscissas. When investigating the combination of different frequencies to a resultant effect, this rational scale, which is the scale of acoustics, is preferable.*

---

* The usual way of recording spectra, with the wave-length, or the frequency as abscissas, is irrational; one wave-length in the ultraviolet represents a far greater range than in the ultrared. The infinite number of radiations of shorter wave-length, or higher frequency than the visible, are crowded into a finite space, when using wave-length as abscissas, while the lower frequencies or longer waves cover the whole range from the ultrared to infinity. The reverse is the case with the frequency as abscissas. The intensity curve of radiation, measured and recorded with the wave-length as abscissas, is different and its maximum at a different point, than the intensity of the same radiation, plotted with the frequency as abscissas. The rational scale of any periodic quantity is the geometric scale, where equal intervals represent equal percentual increase or decrease; that is, the logarithmic scale. This was realized long before science existed: it is the scale used in music, with the octave; that is, log 2, as abscissas.


RED
ORANGE
YELLOW
GREEN
BLUE
INDIGO
VIOLET
76
69.1
67.2
62.4
57.8
54.6
49.2
43.55
40.8
40.5
39
Li
Li
Na
Tl
In
0.9
0.88
0.86
0.84
0.82
0.8
0.78
0.76
0.74
0.72
0.7
0.68
0.66
0.64
0.62
0.6
0.58
lg λ
f_{41}
fis
g
gis
a
b
h_{41}
c_{42}
cis
d
dis
e
f
fis
g_{42}

In Fig. 2 the mercury spectrum is given in polar coördinates with the octave, or the ratio of wave-lengths 2 ÷ 1, represented by 360°. For illustration, the frequency denotations of acoustics are recorded in Figs. 1 and 2; that is, one tone represents 30°.

For comparison the spectrum lines of Li, Na, Tl, and In are also shown.

Of the spectrum lines of mercury of approximate wave lengths:

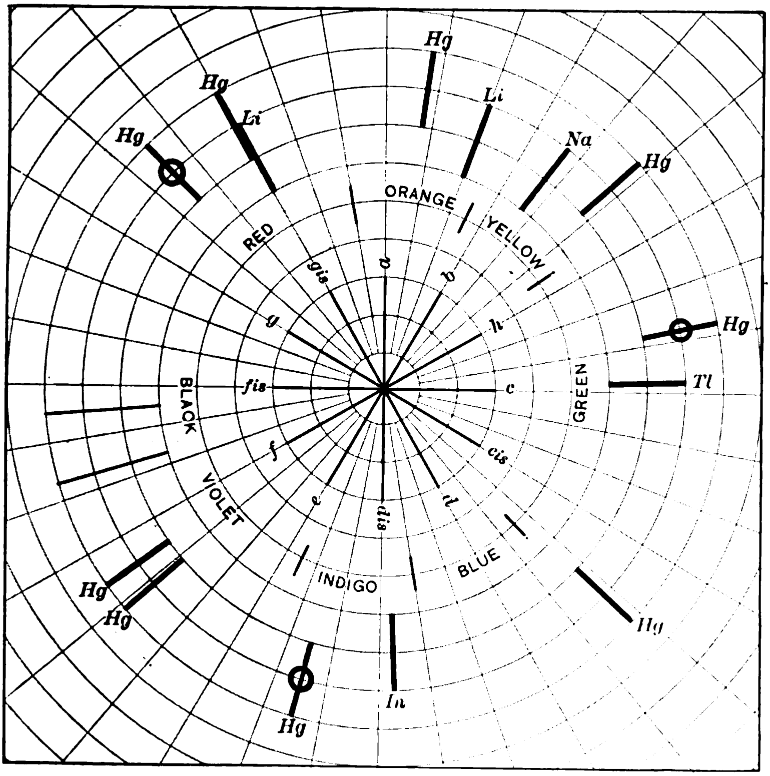


FIG. 2

40.5; 40.8; violet	43.55; blue	49.2; 54.6; green	57.8; yellow	62.4; orange	67.2; 69.1; red*,

the lines:

Blue.... .... 43.55
Green............................. 54.6
Yellow............................ 57.8

---

* The wave-lengths of these red lines require re-determination. Some of the other lines are twins.

are the most prominent. The three red lines, and many more red lines, appear only at higher temperature, as in the Heraeus quartz lamp.

The three spectrum lines of mercury:

Blue	43.55
Green	54.6
Red	69.1

which are about equidistant and therefore appear the most suitable as primary colors for a standard of light.

Two low-temperature mercury lamps would be required for the blue and the green, and one high-temperature quartz lamp for the red. These would be maintained at constant radiation by maintaining the current constant, and also the condition of ventilation and surrounding temperature.

Resolved by a prism, the blue line of the first, the green of the second, and the red of the third lamp are thrown on the same white screen, and their radiation energy measured separately. What energy proportion to select for the three colors, to give a color suitable for a primary standard, remains to be investigated. Probably a yellowish-white would industrially be most convenient.

It is interesting to note that such a selection of three primary colors as components of a standard of light would also allow an exact numerical expression of the physiological color of any light, by the ratio of the three intensities, $a \div b \div c$; that is, the color of light could be measured by varying the intensities of the three standard wave-lengths until their combination, on the white screen, becomes identical in color with the observed light.

A paper to be presented at the 226th Meeting of the American Institute of Electrical Engineers New York, March 13, 1908.

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(Subject to final revision for the Transactions.)

NOTES ON ELECTRIC HAULAGE OF CANAL BOATS*

BY LEWIS B. STILLWELL AND H. ST. CLAIR PUTNAM

The following notes are based upon the results of tests conducted by the authors during the autumn months of 1907 on a section of the Lehigh Canal near Mauch Chunk, Pennsylvania. The object of the tests was to determine:

a. Pull required to propel canal boats at various speeds and with varying numbers of boats in tow.

b. The relative merits, for the purpose contemplated, of locomotives supplied by trolley and operating upon a track of 42-in. gauge, and a monorail system.

c. The best speed and length of tow as fixed by physical conditions.

d. The power required to operate the canal between Coalport and Bristol.

e. The equipment required for such operation.

The data presented in this paper are included under the headings "a", "b", and "c" of the foregoing summary.

The upper section of the canal from Lock No. 2 to Coalport, a distance of 10,095 ft., is equipped with the "Locomotive System". The plan and profile of this section of the canal are shown in Fig. 2. On this section an ordinary mining locomotive is used. Two locomotives were tested, each weighing under test conditions 16,000 lb. without testing instrument equipment and crew. Each locomotive is equipped with two direct-current motors of 28 h-p., operating on 500-volt trolley circuits. The locomotive wheels are 28 in. in diameter and gear-ratio of 69/15. The wheel-base is 44 in. The outline drawing of this locomotive is shown in Fig. 6.

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* By the courtesy of Mr. W. A. Lathrop, President of the Lehigh Coal & Navigation Company, for whom the tests were made, we are permitted to present to the Institute such results of our investigation as are not purely local in their significance but comprise data more or less applicable to the general problem of electric operation of canals.

The locomotives were operated on a track of 42-in. gauge and ballasted on the river section with broken stone, elsewhere with gravel. Forty-pound rails were used. The track was uneven and comparatively rough.

On this section, two levels of the canal, aggregating 5600 ft. in length, were in the open river exposed to the river currents. The voltage of the trolley circuits was varied to obtain various towage speeds; an experimental generating plant, connected as shown in diagram No. 9, being used as a source of power supply.

The section of the canal from Lock No. 3 to Lock No. 7, a distance of 10,555 ft., was equipped with the " Monorail System " illustrated in Fig. 3. On this section three traction machines were used. These machines are hereinafter designated " Tractors." Two of these tractors (Nos. 1 and 2) were manufactured in this country. The electric equipment of each comprised one direct-current 40-h.p. motor. The gear-ratio was 5.78 to 1; diameter of wheels 12 in., and length of wheel-base 42 in. The construction is illustrated in Fig. 7. The ratio of leverage on lever wheels was 4.7 to 1; that is to say, the lower wheels are pressed upward against the lower face of the rail with a force 4.7 times the drag on the tow line. The adhesion of the machine, therefore, is a function not only of its weight but also of the pull which it exerts. Each tractor weighs 6,450 lb., and, under test conditions with instruments and crew, 7,350 lb. Tractor No. 3 was manufactured in Paris, and equipped with one 25-h.p. mining motor. Its wheels are 11.25 in. in diameter, gear-ratio is 3.4 to 1, and wheel-base 42 in. The general design is the same as that of Tractor No. 1 and is shown in Fig. 7.

Owing to the fact that the frame of this tractor had not been designed to receive a motor of the exact dimensions of that with which it was equipped, it was impossible to locate the motor in its proper position; it was necessary, therefore, to use 500 lb. counterweight to secure equilibrium of the machine. The weight of the tractor complete was 5,093 lb.; including counterweight, test apparatus, and crew, 6,493 lb.

The mechanical construction and workmanship of Tractor 3 made it superior to Tractors Nos. 1 and 2, as was evidenced

not only by inspection but also very conclusively by the results of tests. In our comparative calculations of power required respectively by the locomotive and monorail systems, therefore, we have used the results obtained in using Tractor No. 3.

The tractors were operated upon a monorail supported at a height of 4 ft. above the ground by steel posts placed at intervals of 18 ft. The rail, as used in the installation at Mauch Chunk, is an ordinary 10-in. I-beam weighing 75 lb. to the yard. The monorail with supports and braces complete weigh 120 lb. per yard and is erected along the canal outside the tow-path. The construction is illustrated in Fig. 4.

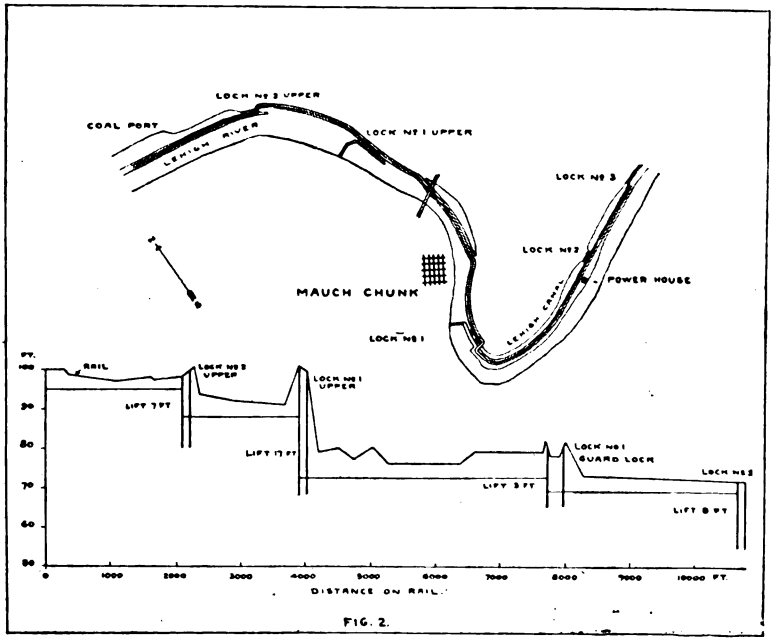
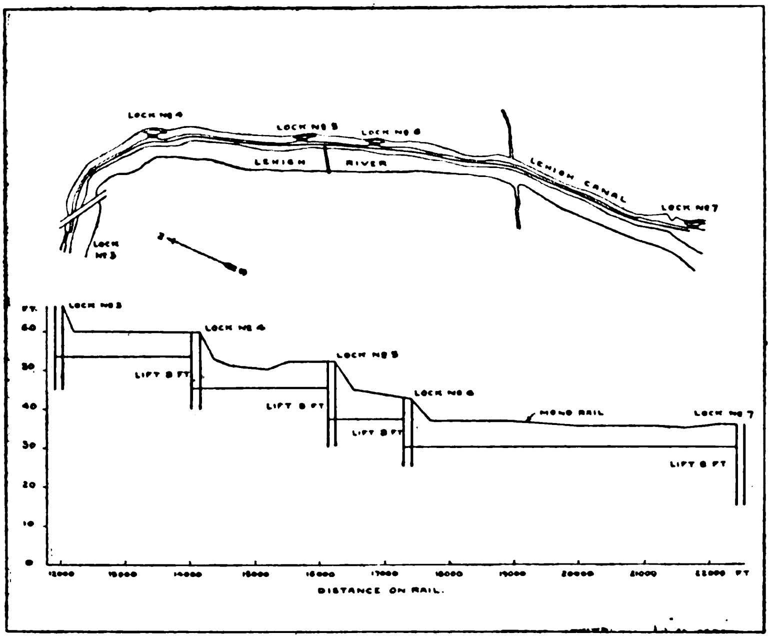


FIG. 2

A fourth tractor, No. 4, built in Paris, was also subjected to certain tests. This machine, without testing crew and instruments, weighed 3,465 lb. It was equipped with one direct-current 500-volt motor of 15 h.p. The diameter of wheels was 12.75 in. and the wheel base 24 in. This machine is illustrated in Fig. 8.

For this smaller machine a section of monorail tract 1,200 ft.


LOCK NO 4
LOCK NO 5
LOCK NO 6
LEHIGH RIVER
LEHIGH CANAL
LOCK NO 7
LOCK NO 3
FT.
60
50
40
30
20
10
0
LOCK NO 3
LOCK NO 4
LIFT 8 FT
LOCK NO 5
LIFT 8 FT
LOCK NO 6
LIFT 8 FT
MONO RAIL
LOCK NO 7
LIFT 8 FT
12000
13000
14000
15000
16000
17000
18000
19000
20000
21000
22000 FT
DISTANCE ON RAIL.

[FIG. 3

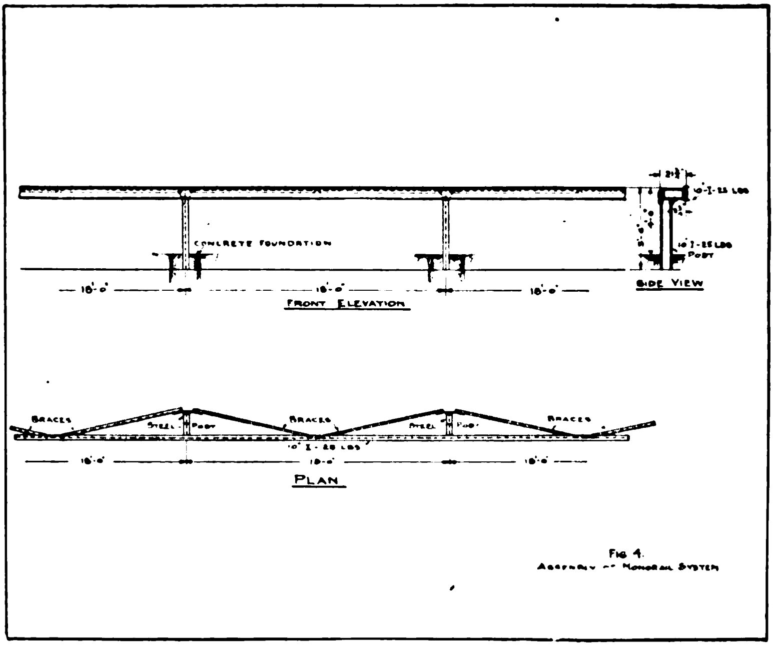

CONCRETE FOUNDATION
18'-0"
18'-0"
18'-0"
FRONT ELEVATION
21½"
10"-I-25 LBS
10" I-25 LBS POST
SIDE VIEW
BRACES
STEEL POST
BRACES
STEEL POST
BRACES
10" I-25 LBS
18'-0"
18'-0"
18'-0"
PLAN
FIG 4.
ASSEMBLY OF MONORAIL SYSTEM

FIG. 4

long was erected on wooden posts between Locks Nos. 2 and 3. The rail in this case was a 7-in. I-beam, weighing 45 lb. per yard, and was erected at a height of 4 ft. from the ground. It was not deemed necessary to undertake complete tests of Tractor 4, as certain preliminary tests showed that the machine was not adequate in mechanical strength and power equipment for the service. Volt and ampere readings were made, however, in connection with dynamometer readings and from these the approximate performance of the machine was determined.

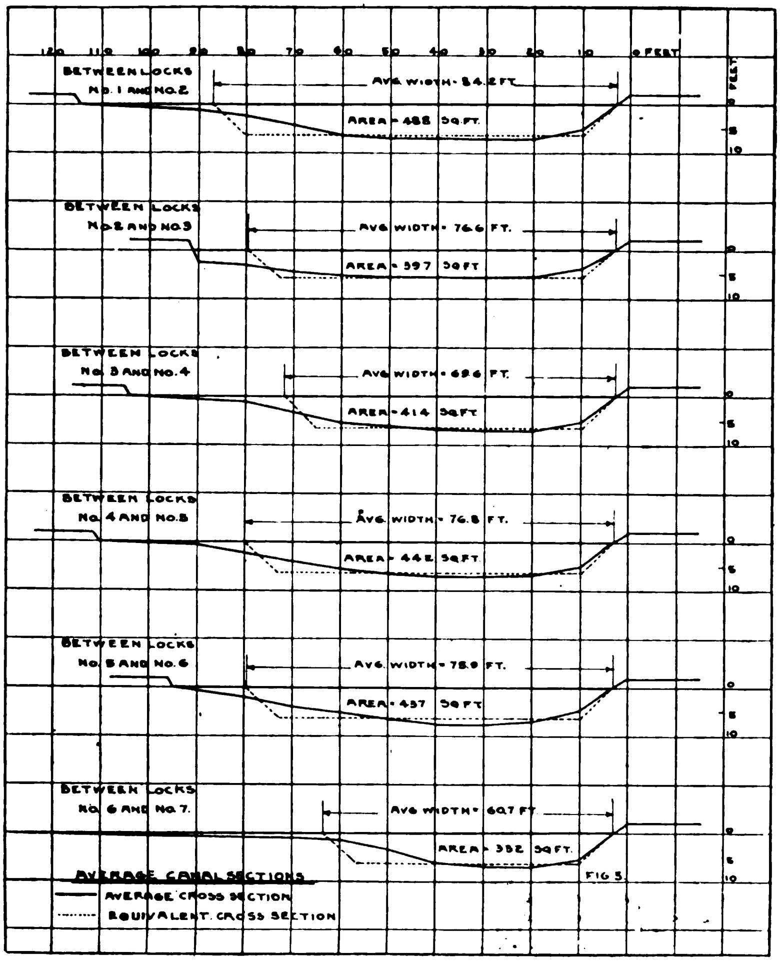


FIG. 5

The following instruments were used in making the tests:

Direct-current graphic recording wattmeter with time attachment. This wattmeter was also equipped with a signal pen used to record distances and special points by means of a push button. Weston ammeter. Weston voltmeter. Three spring dynamometers. Two integrating wattmeters used to measure respectively the energy delivered to the monorail and locomotive sections.

Distance marks were located at distances of 52.8 ft. along the track. As each point was passed by the machine undergoing test, a push-button record was made by the signal pen in the graphic recording wattmeter and at the same instant the voltmeter and dynamometer were read by the test crew. In addition, during one complete run, the angle formed by the tow-rope and the center line of the track was determined at each distance point by measuring the distance from the center of the track to a fixed length of tow-line. All test results are corrected for this angle, and the tow-line pulls stated are the

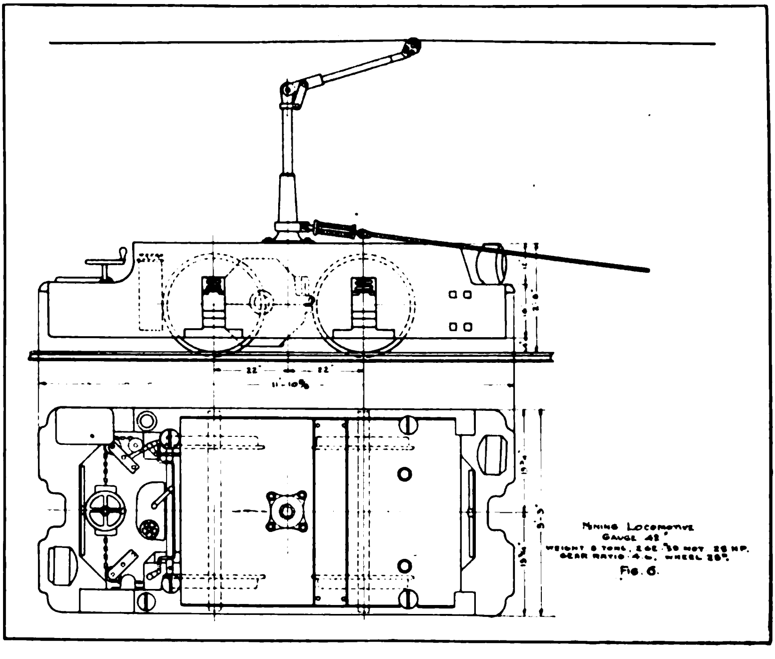

22"
22"
11'-10⅝"
MINING LOCOMOTIVE
GAUGE 42"
WEIGHT 8 TONS, 2 GE 30 MOT. 28 HP.
GEAR RATIO 4.6, WHEEL 28".
FIG. 6.

FIG. 6

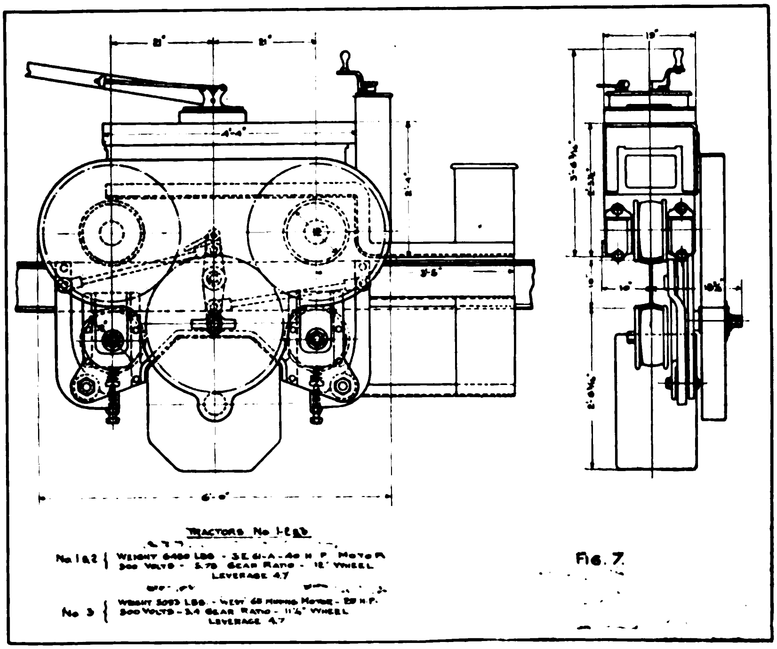

8'
8'
4'-4"
8'-4"
3'-8"
6'-0"
19"
3'-6 3/16"
10"
10¾"
TRACTORS No 1-2 & 3
No 1 & 2 { WEIGHT 6480 LBS - G.E. 61-A - 40 H P MOTOR
500 VOLTS - 5.78 GEAR RATIO - 12" WHEEL
LEVERAGE 4.7
No 3 { WEIGHT 5093 LBS. - WEST' 68 MINING MOTOR - 25 H.P.
500 VOLTS - 3.4 GEAR RATIO - 11¼" WHEEL
LEVERAGE 4.7
FIG. 7

FIG. 7

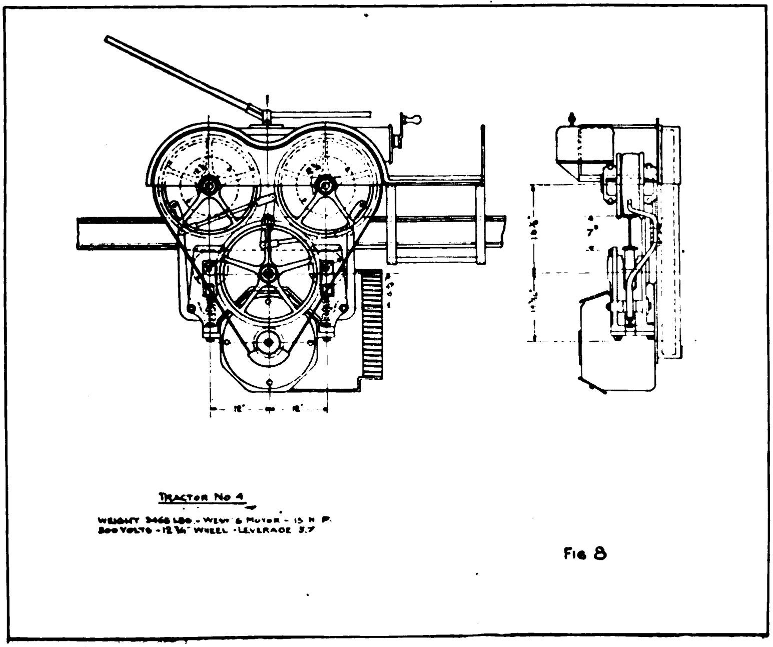

10¾"
7"
10¾"
12"
12"
TRACTOR No 4
WEIGHT 3466 LBS. - WEST' 6 MOTOR - 15 H P.
500 VOLTS - 12¼" WHEEL - LEVERAGE 3.7
FIG 8

FIG. 8

effective pulls in the direction of motion. In the tests the tow-line was approximately 200 ft. long. Typical records such as were made in each test, are shown in Fig. 11.

Four canal boats were loaded and used in all comparative tests made. The weight in net tons, dimensions, and draft were as follows:

TABLE I

Boat	Loaded	Empty	Length	Width	Draft
1	137 tons	23.5 tons	87 ft. 6 in.	10 ft. 5 in.	5 ft. 1.875 in.
2	139 "	23.0 "	87 ft. 6 "	10 ft. 5 "	5 ft. 2.5 "
3	137 "	24.2 "	87 ft. 6 "	10 ft. 5 "	5 ft. 2.625 "
4	135 "	24.2 "	87 ft. 6 "	10 ft. 5 "	5 ft. 1.75 "

These boats in the order named were used in all four-boat tests.

Boats 3 and 4 were used in one-boat tests.

Boats 1 and 2 were used in two-boat tests. In the later tests boats 1 and 2 were equipped with the " Erie Steering Gear " hereinafter described.

In addition to tests of the four boats above referred to, the regular canal traffic was handled by the test machines on their respective sections during the months of October and November and a part of September. Complete tests were made from time to time as opportunity offered, until it was thought that sufficient data had been collected. We have found it necessary to make use of these miscellaneous tests to a limited extent only.

The velocity of the current of water flowing in each section of the canal was determined at the time the tests were made, but to obtain an average value for towing resistance, including the effect of this current and also of track grade, all tests were made in both directions over each section of the canal. The average results are used in our calculations.

Effective tow-rope pulls required. The effective tow-rope pulls as determined by dynamometer tests and corrected for the rope-angle for four-, two-, and one-boat tests, both light and loaded, are given in Fig. 12 and Fig. 13.

The following table shows the average results obtained at the average towage speeds attained in tests:

TABLE II

Boats	Weight tons (2000 lb.)	Average speed in mi. per hr.	Effective pull pounds	Constant ($C\ V^2\ T$)
Four boats loaded	548	2.98	2200	0.452
Two boats loaded	274	3.62	1500	0.418
One boat loaded	137	4.00	1000	0.456
Four boats empty	95	4.00	1010	0.664
Two boats empty	47.5	4.20	560	0.668
One boat empty	23.8	5.00	400	0.673

In the majority of the two-boat tests, the boats were equipped with the so-called Erie steering gear. With this gear the second boat is used as a rudder for the first boat, to which it is tightly lashed. The arrangement is illustrated in Fig. 10.

The effect, so far as resistance of the water is concerned, is a reduction of approximately eight per cent. in the pull required; in addition to which saving the boats are kept in better alignment and are under better control. In the majority of the four-boat-tests, the first two boats were equipped with the Erie steering gear, but this beneficial effect as regards reduction of pull required, was apparently lost, owing probably to the effect of the drag of the last two boats, which tended to alter the position of the first two with reference to the line of motion.

From Table II it appears that for boats, such as are used on the Lehigh and Delaware canals, the effective tow-rope pull in pounds, required for any number of loaded boats, is expressed approximately by the formula $0.45\ V^2\ T$, and for empty boats by $0.67\ V^2\ T$, where V is the speed in miles per hour and T the total tons (2000 lb.). No tests were made of partly loaded boats, but for these the following formula must be approximately correct. Effective pull required equals

$$\left(0.67 - \frac{0.22 \text{ x net load per boat}}{113}\right) V^2\ T.$$

It was impracticable with the facilities at hand to secure reliable data as to the effect of the ratio of boat-section to canal-section. The immersed cross-section of a loaded boat is 54 sq. ft., while the average cross-section of a canal, on those sections upon which most of the tests were made, is 440 sq. ft.;

the ratio of section being practically 1 to 8 (Fig. 5). The current in the open-river section is so varied that reliable results expressing difference in pull required in the comparatively narrow sections and in these wider sections could not be obtained.

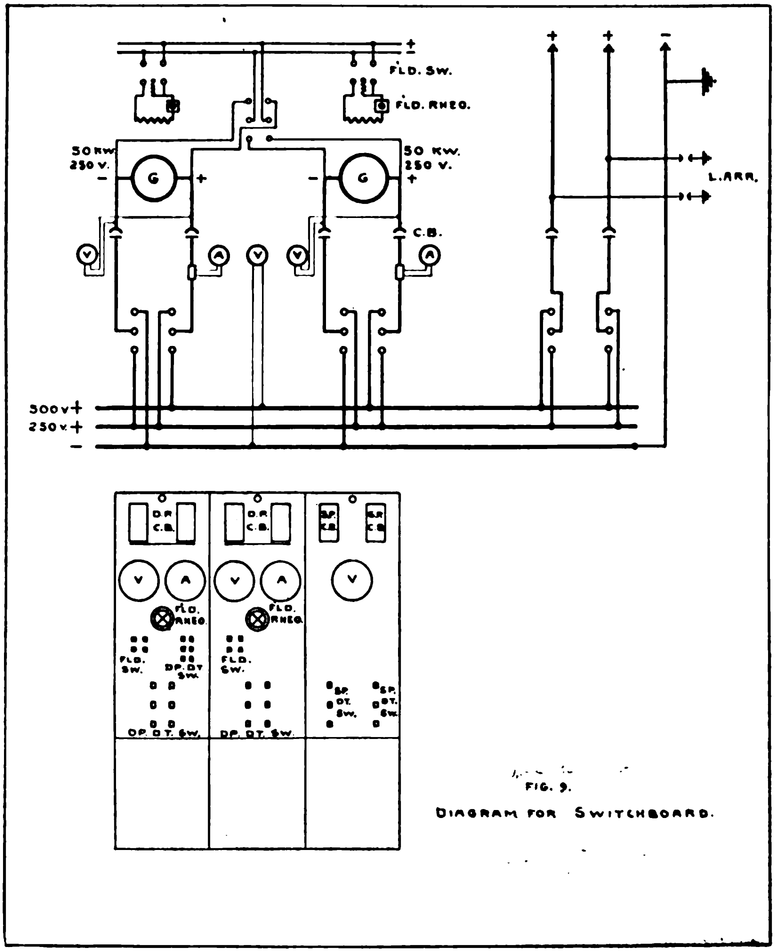


FIG. 9

ACCELERATION AND MAXIMUM ROPE PULLS

Compared with electric railway operation, the rate of acceleration practicable of attainment in towing canal boats is low. Acceleration, however, is relatively unimportant, as the time of run is long compared with the time consumed in accelera-

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tion. The greatest pull is exerted when the last control-point is reached, but this does not greatly exceed the pull required at full running speeds.

Table III gives the maximum and average results obtained in four-, two-, and one-boat tests, both loaded and empty.

TABLE III.—ACCELERATION AND ROPE PULL
(Pulls not corrected for rope angle.)

	Acceleration miles per hr. per sec.		Pull lb. at end of acceleration		Average pull lb. running	
	Ave.	Max.	Ave.	Max.	Ave.	Max.
4 boats loaded	0.0243	0.045	2370	3100	1990	2300
4 boats empty	0.0975	0.142	1220	2100	1040	1250
2 boats loaded	0.0594	0.101	2240	3100	1500	1700
2 boats empty	0.0995	0.135	850	1150	680	1100
1 boat loaded	0.0667	0.103	1190	1800	650	1000
1 boat empty	0.1090	0.173	730	1100	625	900

TOWING MACHINES TESTED.

In most of our tests Mining Locomotive 15 and Tractors 1 and 3 were used. Comparison was made at speeds and effective pulls as nearly identical as was found practicable.

As to meet these conditions the various machines tested required different operating energy, and as change in the energy affected the motor efficiency, the electric losses in the motors in all cases have been deducted from the kilowatt input in determining the mechanical efficiency of the machines. The mechanical loss of the motors and gears in each case is charged against the respective machines. The tow-line pull in all cases has been corrected to the effective pull in pounds in the direction of motion.

TABLE IV
EFFICIENCY OF TOWING MACHINES

	Effective pull 1000 lb.	Effective pull 2000 lb.	Effective pull 3000 lb.
Mining Locomotive	80%	83.5%	84%
Tractor 1	68	73.3	74.8
Tractor 3	73	77.2	77.5

Expressed in another way the results are summarized in Table V.

The results of these tests are perhaps more clearly illustrated in Fig. 14, in which the inputs to the towing machines are reduced to equivalent draw-bar pulls.

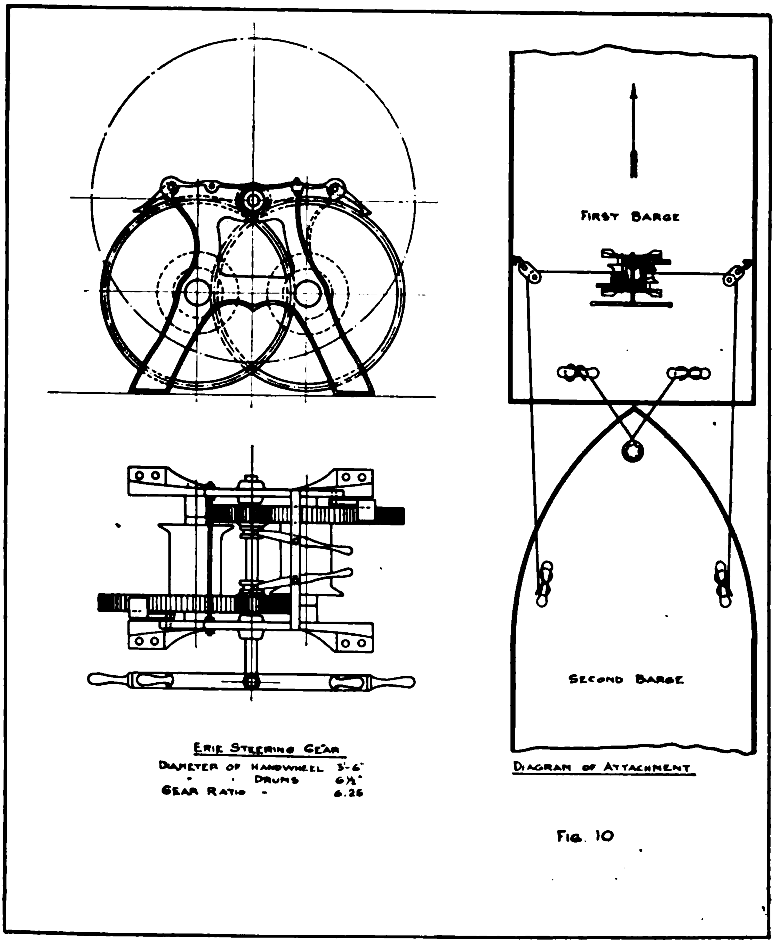

Fig. 10

The performance of the three towing machines, running light without load, is shown in Table VI. For convenience, the input to the machines is expressed both in kilowatts and equivalent draw-bar pull in pounds. The values stated include all mechanical friction of motors, gears, and track, but do not include the electrical losses in the motors.

TABLE V

EQUIVALENT PULL IN POUNDS LOST IN MACHINE AND TRACK FRICTION WHEN DELIVERING

	Effective pull 1000 lb.	Effective pull 2000 lb.	Effective pull 3000 lb.
Mining Locomotive	250	400	590
Tractor 1	450	700	1000
Tractor 3	375	600	890

TABLE VI

Speed miles per hour	Mechanical Friction Running Light					
	Kilowatts			Equivalent drawbar pull pounds		
	Mining Loco.	Tractor 3	Tractor 2	Mining Loco.	Tractor 3	Tractor 2
3	0.88	.98	1.44	82	91	134
4	1.28	1.40	2.16	90	98	151
5	1.70	1.82	2.90	95	102	163
6	2.17	2.32	3.68	101	108	172
8	3.20	3.41	....	112	119	...
10	4.40	....	....	123	...	...

The results of these tests are illustrated in Fig. 13.

It will be noted that in running without load the machines preserve approximately the same relationship as they do when operating under load conditions, though the relative magnitude of the values are changed. When developing large draw-bar pulls, the mechanical losses in Tractor 3 are 50 per cent. in excess of those of the Mining Locomotive. Mechanical losses in Tractor 1 exceed those of the Mining Locomotive by from 70 to 80 per cent. Under light running conditions these excess losses are reduced to about 7 per cent. in the case of Tractor 3, though the excess remains approximately 70 per cent. for Tractor .1.

The running light losses are, in themselves, relatively unimportant, as the amount of power required is small and the amount of idle running relatively very small; but, as showing errors in design and workmanship, which are corroborated by the results of the heavy load tests, they are important. We shall not here enter into a theoretical discussion of the design of these Tractor machines. It is apparent that their mechanical design can be improved materially. When running light, it would be reasonable to expect that these machines, if properly designed, should effect a saving in power consumed almost

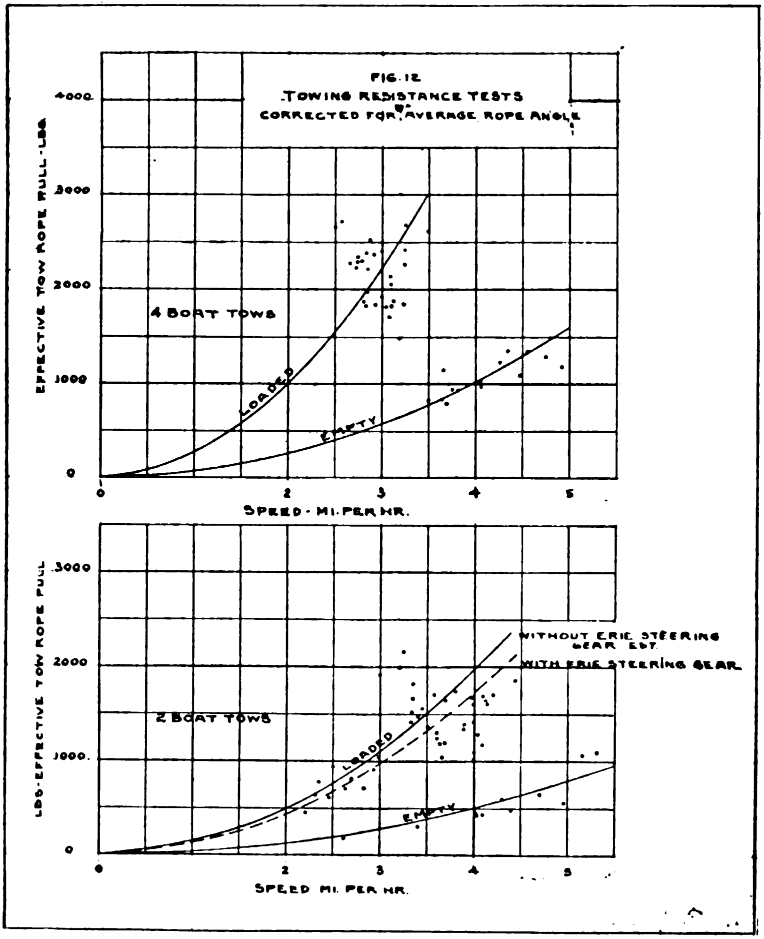

FIG 12

proportional to their less weight as compared with the Mining Locomotive.

Under load conditions, especially as the draw-bar pull approaches the maximum of which the locomotive is capable, the latter machine, theoretically, should show the higher mechanical efficiency. This is due to the fact that when the Mining Locomotive utilizes its entire weight for traction; to obtain a similar draw-bar pull with the Tractor, the two driving wheels on top must have a pressure upon them equal to the weight of the Mining Locomotive. As the weight of the Tractor is 10,000 lb. less than that of the Mining Locomotive, a pressure of at least

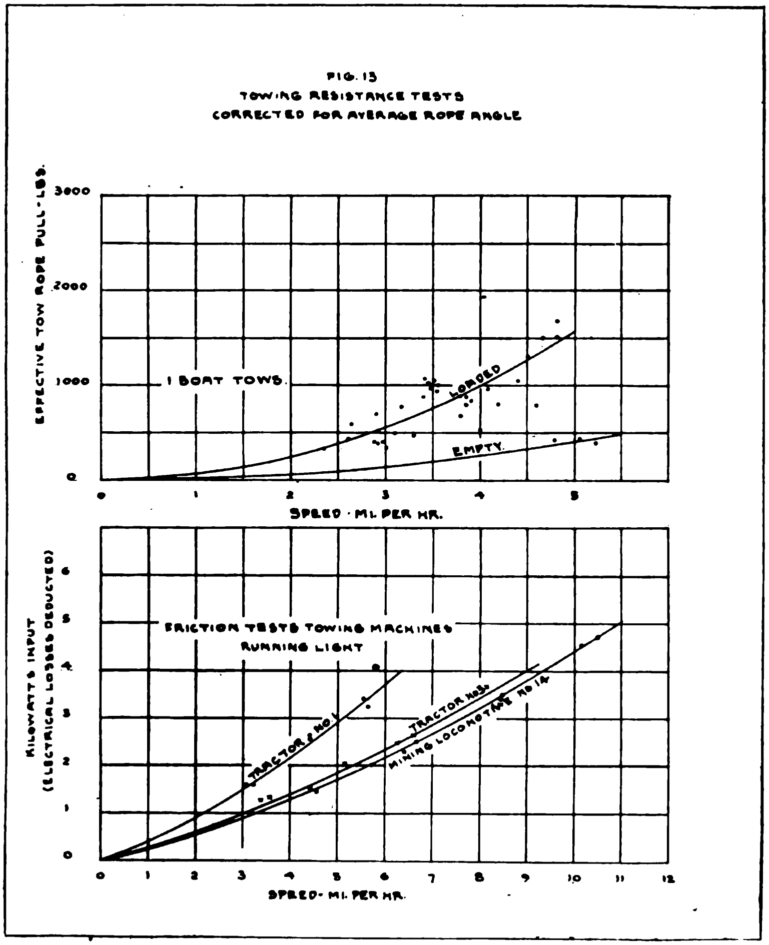

FIG. 13

10,000 lb. must be exerted on the lower or pressure wheels. It is evident, therefore, that the track and rolling friction of the Tractor must be greater than that of the Mining Locomotive by the amount of this excess pressure on the track. Considering track friction only, this excess should amount to about 60 per cent. at maximum pull. The tests of Tractor 3 show an excess of about 50 per cent. at 3,000 lb. rope pull, though the test results are not exactly comparable, as motor and gear frictions are included and are different in the two machines.

Assuming that the Tractor may be so designed that its aggregate mechanical friction per ton of weight does not exceed that of the Mining Locomotive, it is obvious that when running light less power should be required to move the former at a given speed than is required by the latter. Assuming good mechanical design, it follows that the Tractor under light loads

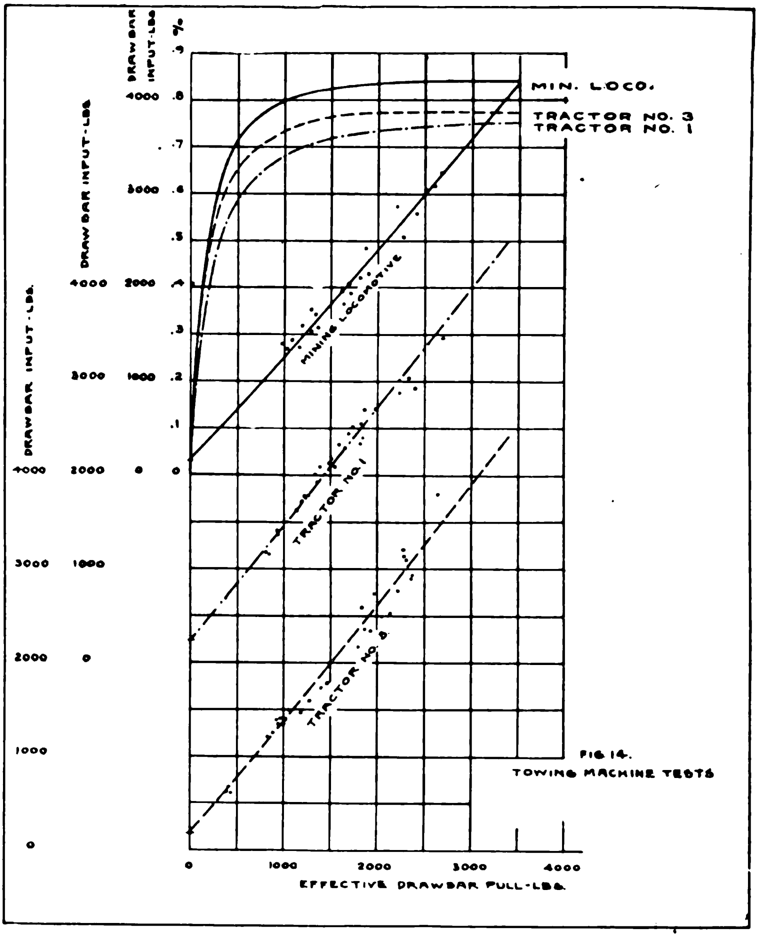

Fig. 14

should be more efficient than the Mining Locomotive, and that at some load between the limits of very light load and full load, the efficiency curves of the two machines should cross. So far as comparative efficiency is concerned, therefore, great care must be taken in designing the Tractor, to minimize friction losses if it is expected to make a good showing as compared with the Mining Locomotive.

In order to assist in determining the cause of the apparently excessive friction of these Tractors, at low rope-pulls and when running light, tests were made on a wet rail to determine the relative amount of reduction in friction due to a bad rail, and other tests made pulling the Tractors with the gears and motor disconnected. The results of these tests are illustrated in Fig. 15 and show that at a speed of six miles an hour the wet rail effects a saving of about 16 per cent. in total friction, running light, and at the same speed the gear and motor friction amounted to 28 per cent. of the total. It is apparent from the tests that frictions at light loads are relatively small and at large pulls the difference is to a large extent lost as the mechanical friction approximates the theoretical amount to be expected from the pull exerted.

It would seem that the mechanical efficiency of tractors of this type might be improved by giving attention to the following facts:

1. An increase in the size of wheels would tend to decrease losses.
2. The wheel-base should be long and the " flange clearance " small.
3. The mechanical construction must be such that alignment of all bearings is preserved under all conditions of operation.
4. The point of rope attachment should be carefully selected in order to reduce flange friction to a minimum.
5. The rail surface should be as good as on ordinary railway tracks, and the construction should be such as to minimize vibration.
6. The use of guides for the pressure wheels should be avoided if practicable. If used, the vertical motion in the guides for the pressure wheels should be free.
7. The pressure wheels should have no flange.
8. Arrangements for oiling the bearings of tractors as well as of locomotives should follow railroad practice.

Speed limitations and length of tow. In hauling canal boats by mules, the speeds attained vary from 1.25 to 2 miles an hour. When the current assists, the speed exceeds these amounts; when the tow is against the current, the speed sometimes drops very low. Dynamometer tests were made, and it was determined that in starting a tow, a team of good mules could exert momentary pull approximating 800 lbs. This is maintained but momentarily.

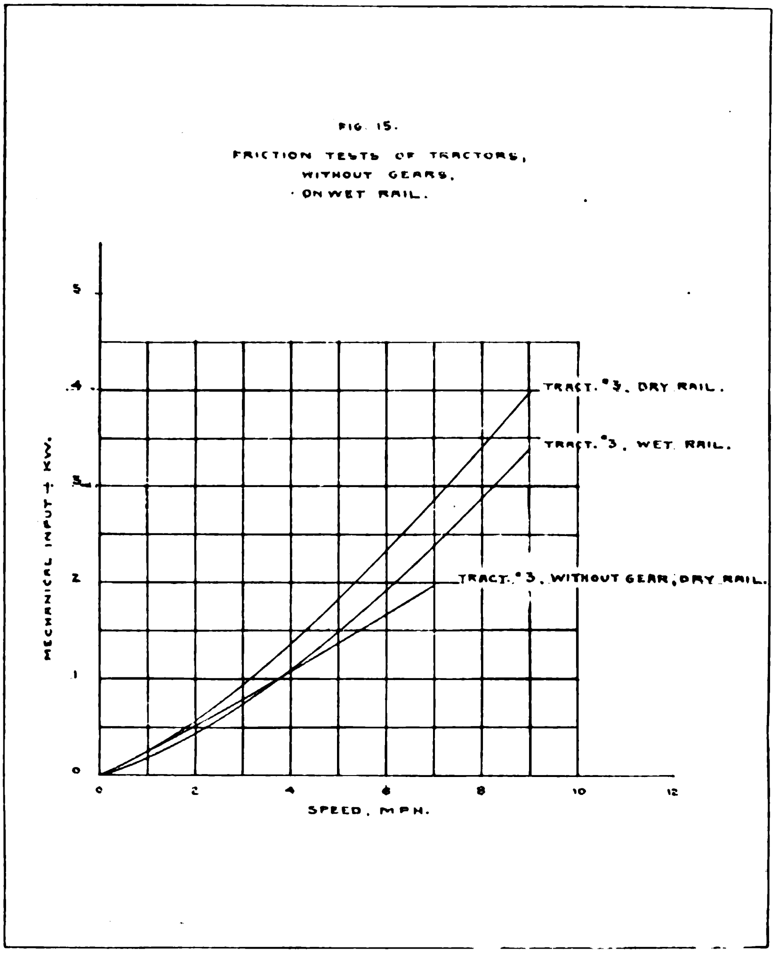

Fig. 15

The average speed at which a team of mules draws a one-boat tow approximates 1.75 miles an hour and does not exceed 2 miles an hour in still water. The pull required at 2 miles an hour, as determined by the tests in which the Mining Locomotive and Tractors were used, is 250 lb.; at 1.75 miles an hour it is 190 lb., and at 1.5 miles an hour it approximates 140 lb. The curves expressing the relation of pull and speed for tows of various length are shown in Fig. 16.

Tests were made to determine the practicable limits of speed when towing is done with towing machines. These limits depend upon the following:

a. Ability to steer the boats.

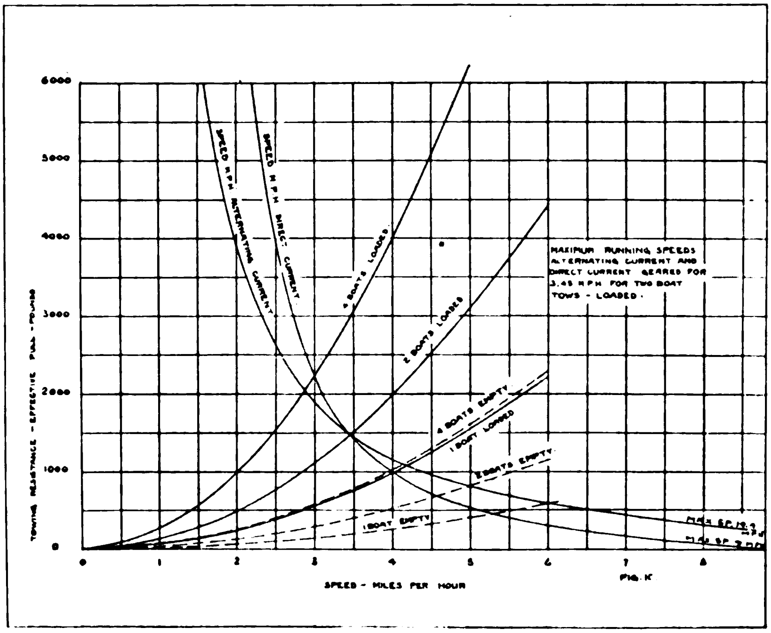

FIG. 16

b. Wash of canal banks.

c. Time required for locking.

d. Tonnage capacity and length of tow.

The selection of a best speed depends also upon the number of boats which must pass through the canal in a given time to handle its business. This will be referred to further under the heading "*Tonnage Capacity and Length of Tow*".

Ability to steer boats. Single boats, both loaded and empty, were tested at speeds slightly exceeding 5 miles an hour and no difficulty was experienced in steering them.

Two-boat tows loaded were operated at speeds up to 4.5 miles an hour. With the Erie steering gear the boats handled well at this speed, but care had to be exercised by the helmsman to keep his course true. Two-boat tows (light) were operated successfully at a speed of 5.3 miles an hour.

Four-boat tows (loaded), the first two boats being equipped with the Erie steering gear, were operated at a speed of 3.5 miles an hour. At this speed, however, it was necessary for the helmsman to exercise great care to prevent the boats yawing. Four-boat tows, empty, were operated at speeds up to 5 miles an hour, but great difficulty was experienced in steering; the drag of the rear boat's pulling the head boats against the bank in spite of anything the helmsman could do. This was especially noticeable in going around curves convex with reference to the bank upon which the tow-path was located. It was found quite impossible to start four-boat tows on such a curve.

The relations of speed and pull for tows of various lengths, loaded and unloaded, are illustrated in Fig. 16.

Our conclusions in regard to limits of speed, as fixed by conditions of practicable steering, are:

a. Single boats, loaded or empty, can be operated satisfactorily on tangents at speeds exceeding 5 miles an hour, but on the canal for satisfactory working 5 miles an hour is probably about the limit of average speed for such tows.

b. Two-boat tows are handled satisfactorily at speeds of from 3.5 to 4 miles an hour.

c. Four-boat tows loaded can be operated with a fair degree of success at speeds up to 3 miles an hour except on very sharp convex curves.

d. Four-boat tows, light, were found impracticable as tested. It is possible that improved steering gear might remedy the difficulties encountered, except that no conceivable steering-gear would make it possible to handle four-boat tows, light, in a heavy wind.

Wash of canal banks. At the higher speeds covered by the tests a tendency to cause wash of the canal banks was noted. The tests were not of sufficient duration to justify an attempt at estimating the relation of wash and speed.

At a given speed the wash is greatest in narrow sections of the canal. To a certain extent in these narrow sections the speed is automatically regulated; the resistance to the passage of the boat being increased and this resistance immediately reacting upon the series motor used in our tests.

The speed of towing should be under the control of the operator, and to obtain best results the motor used should be capable of operating at any desired speed within the predetermined maximum limits. With equipment of this character, the speed can be regulated on those sections where the wash might otherwise be injurious.

Time required for locking. Tests were made to determine the time required in locking one, two and four boats and to see if the time could be reduced in any way. The following is a typical locking for two- or four-boat tows under test conditions.

TABLE VII

LOCKING TESTS

	Lift 8 ft. Lock No. 4 4 boats		Lift 8 ft. Lock No. 5 2 boats
	First 2 boats Erie steering-gear, minutes	Second 2 boats No gear minutes	First 2 boats Erie gear, minutes
Tow-line let go	00.00	00.00	00.00
First boat entered lock	1.75	....	....
First boat tied in lock	1.25	3.00	2.00
Second boat tied in lock	1.75	3.75	3.50
Upper gate closed (lock emptied)	0.75	.25	1.00
Lower gate opened	2.00	3.50	3.00
First boat started out	.00	.25	.00
Second boat started out	1.75	.25	0.75
First boat out	0.25	1.25	0.25
Steering-gear adjusted	2.00	1.00*	1.50
Started pulling both boats	.00	1.25	....
Both boats out of lock	0.50	0.50	0.25
	12.00	15.00	12.25
Lower gate shut	.50	....	1.00
Upper gate opened	2.00	....	1.75
	2.50		2.75

* Boats tied together only, no steering-gear.

SUMMARY

First two boats	12.00	minutes
Refilling lock	2.50	"
Second two boats	15.00	"
Total four-boat tow	29.50	

The foregoing figures represent average results obtained in tests. During these tests the men handling the boats were working at a speed which they could not be expected to attain in normal service and, therefore, we have based upon the test results estimates of the average time of locking to be expected in ordinary working.

The actual time, as determined by test and our estimate for average conditions, (the latter of which is used in subsequent calculations) is given below:

TABLE VIII

Time locking two-boat locks	* Observed test time	Estimated average time
Time locking four boats	29.5 min.	35 min.
Time locking two boats	12.0 "	15 "
Time locking one boat	8.0 "	10 "

In four-boat locks, with the first two boats and the last two boats equipped with Erie steering-gear, it would not be necessary to disconnect the steering-gear and the time of locking would not greatly exceed that for two boats. An estimate of 20 minutes we think is conservative.

No actual tests of the single-boat locks on the Delaware canal were made using canal boats, but during a trip of inspection the time of all lockings of the launch used were taken, and from these observations the time of locking for canal boats was estimated as follows:

TABLE IX

Coasting into lock, tests 4 and 5	2.75	minutes
Upper gate up (average on trip)	.50	"
Lower gate opened (average on trip)	1.75	"
Boat out, average of tests	1.50	"
	6.50	
Time refilling lock and opening gate	2.75	"
Add for second boat	6.50	"
Adjust steering gear	2.00	"
Two boat tow, total time	17.75	"
Estimated average time	21.00	"

The following table gives the estimated average time for locking with tows of different lengths and with locks of different size as used in our calculations.

TABLE X

	1 boat lock	2 boat lock	4 boat lock
Time locking four boats	45	35	20
Time locking two boats	21	15	12
Time locking one boat	8	10	11

The following table gives the estimated time spent in locking from Coalport to Bristol for tows of different lengths based upon the above estimates of time required per lock. (There are 1 four-boat locks and 47 two-boat locks on the Lehigh Canal and 10 two-boat locks and 12 one-boat locks on the Delaware Canal.)

TABLE XI

Four-boat tows, hours one way	42.6
Two-boat tows, hours one way	18.7
One-boat tows, hours one way	11.3

Conclusions. The following is a tabulation of the speeds recommended for tows varying from one to four boats, loaded and empty, assuming, (*a*), that direct-current series motors are employed, and, (*b*), that single-phase alternating-current motors of the compensated type be used.

TABLE XII
MAXIMUM SPEED BETWEEN LOCKS

	Direct current	Alternating current
Four boats loaded	3.00	2.88
Four boats empty	4.00	4.20
Two boats loaded	3.45	3.45
Two boats empty	4.60	5.00
One boat loaded	4.00	4.20
One boat empty	5.30	6.00

Our conclusions in respect to speeds are based upon the observed facts as regards ability to steer boats, the wash of canal banks, the relative time required in locking, and between locks and the tonnage capacity of the canal as affected by the length of tow.

The speeds recommended for direct-current and alternating-current motor equipment respectively, differ by reason of the different speed characteristics of the motors of these respective types. The speed characteristic of the direct-current motor used is that of the series motor on Tractor 1 as used during the tests. The speed characteristics of the alternating-current

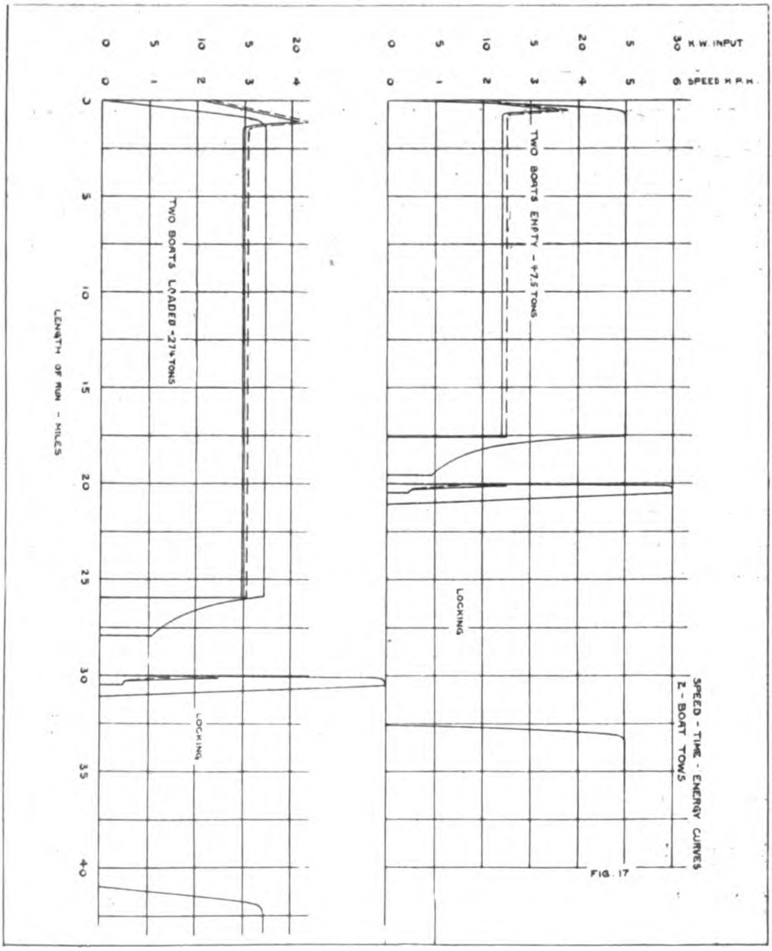

Fig. 17

motor are those of a typical series, compensated, 25-cycle motor. In Fig. 16 the speed curves of these two motors are plotted upon the assumption that the gear-ratios selected are such as will give the same speed for the two contrasted equipments in pulling a tow of two loaded boats, the length of tow being that which, from a purely physical consideration of the problem, appears best.

We have assumed the same speed characteristics of electrical equipment in comparing the mining locomotive with the tractors. The motors with which these respective machines were equipped during tests did not have identical speed characteristics; but there is no reason why they could not be so designed, and the assumption simplifies the general comparison with two types of towing machines.

Tonnage capacity and length of tow. As the length of tow limits the practicable running speed and determines the time consumed in locking, the length of the tow directly affects the tonange capacity of the canal. The maximum running speeds described above, and shown graphically in Fig. 16, give average running speeds which were determined from speed-time curves as shown in Fig. 17. The following table gives the average time required for four-, two-, and one-boat tows to make the round trip from Coalport to Bristol loaded and return empty.

TABLE XIII

TIME IN TRANSIT OVER ENTIRE CANAL—106.2 MILES, WITH EXISTING LOCKS

System of Operations	Direct current			Alternating current		
Number of boats in tow	Four boats	Two boats	One boat	Four boats	Two boats	One boat
Time locking, down	42.6	18.7	11.3	42.6	18.7	11.3
Time between locks, down	34.8	30.2	25.8	36.3	30.2	24.6
Time locking, up	42.6	18.7	11.3	42.6	18.7	11.3
Time between locks, up	25.8	22.5	19.4	24.9	20.6	17.1
Add 10% contingencies	14.2	8.9	7.2	14.6	8.8	6.7
Total in transit, round trip	160.0	99.0	75.0	161.0	97.0	71.0

In order to handle a definite amount of freight, it is evident that a definite number of boats will have to pass through the canal, whether they are operated in four-, two-, or one-boat tows. The number of boats required for this service, however, will be proportional to the time required for a round trip. With a fixed amount of freight to be handled, therefore, it is evident that fewer boats will be required with one-boat tows on account of the higher average speed. The number of towing machines required for the service is proportional to the round trips required and the time for the round trip.

Table XIV shows the ratio of boats required and towing machines required for a definite traffic with tows of different lengths and locks as now existing on the canal:

TABLE XIV

RATIO BOATS AND TOWING MACHINES REQUIRED

	Direct current			Alternating current		
	Four-boat tows	Two-boat tows	One-boat tows	Four-boat tows	Two-boat tows	One-boat tows
Boats required...	2.25	1.39	1.05	2.27	1.36	1.00
Machines required	0.56	0.70	1.05	0.57	0.68	1.00

The ultimate capacity of the canal is limited by the time required in locking. Table XV expresses the ratio of the ultimate capacities with four-, two-, and one-boat tows. Since boats are moving in both directions, the interval between tows is double the maximum time required in passing through that lock on the canal which requires the maximum time for the towing unit employed. We have prepared this table :

a. On the basis of locks as now existing,

b. All one-boat locks changed to two-boat locks.

c. All locks changed to four-boat locks.

TABLE XV

MAXIMUM TRAFFIC CAPACITY

	Four-boat tows	Two-boat tows	One-boat tows
Existing locks.			
Minimum interval between tows........	90 min.	42 min.	22 min.
Ratio maximum capacity..............	0.98	1.05	1.00
One, changed to two-boat locks.			
Minimum interval between tows........	70 min.	30 min.	22 min.
Ratio maximum capacity..............	1.25	1.47	1.00
All four-boat locks.			
Minimum interval between tows........	40 min.	24 min.	22 min.
Ratio maximum capacity..............	2.20	1.83	1.00

On the Delaware Canal, where there are now 12 single locks, there is practically no gain in capacity by increasing the length of the tow. On the Lehigh Canal the capacity is increased nearly 50 per cent. by using two-boat tows, but only 25 per cent. with four-boat tows. The conversion of all the locks on both canals to four-boat locks would approximately double the capacity.

Power required. Speed-time curves have been constructed for both the mining locomotive and the tractor for the towing speeds selected as most practicable and described under the caption "*Conclusions*" for both single-phase alternating-current motors and direct-current motors. The general character of these curves is illustrated in Fig. 17 for a two-boat tow over an

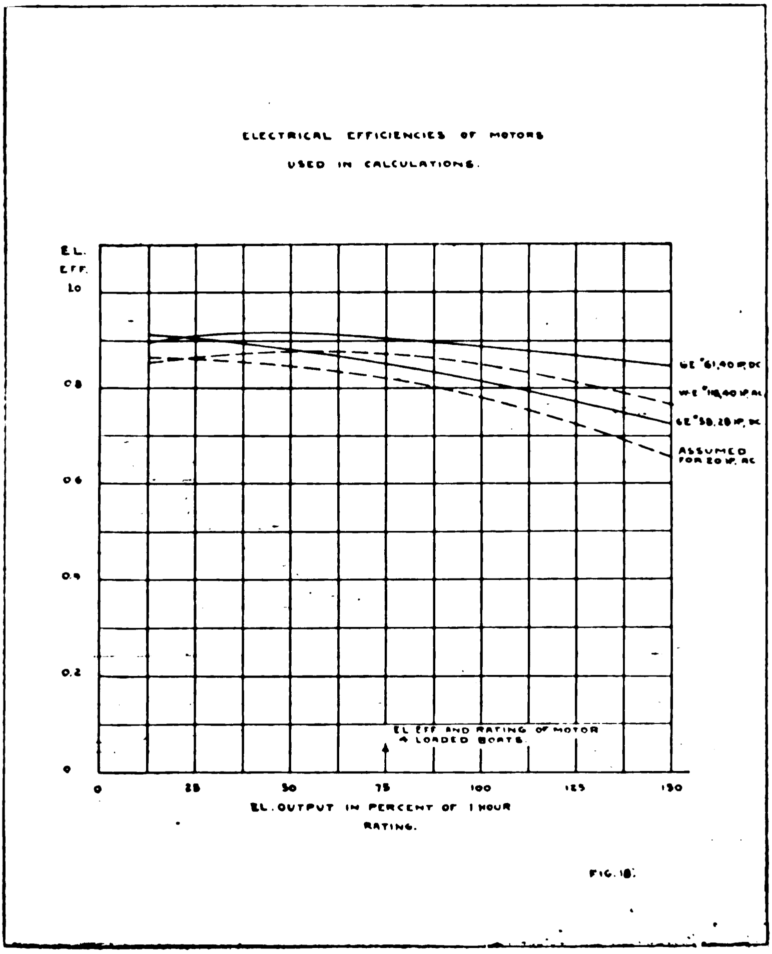

FIG. 18

average run of 1.516 miles. The towing machines as tested were not equipped with motors suitably geared for the speeds desired. We therefore, have assumed these towing machines to be equipped with motors of suitable size and speed and possessing the same efficiencies at their rated loads as the motors furnished by the manufacturers. The motor efficiencies are shown in Fig. 18. These efficiencies have been applied to the mechanical efficiencies of the towing machines, as shown in Fig. 14. We have so applied these efficiencies that the input for a four-boat tow

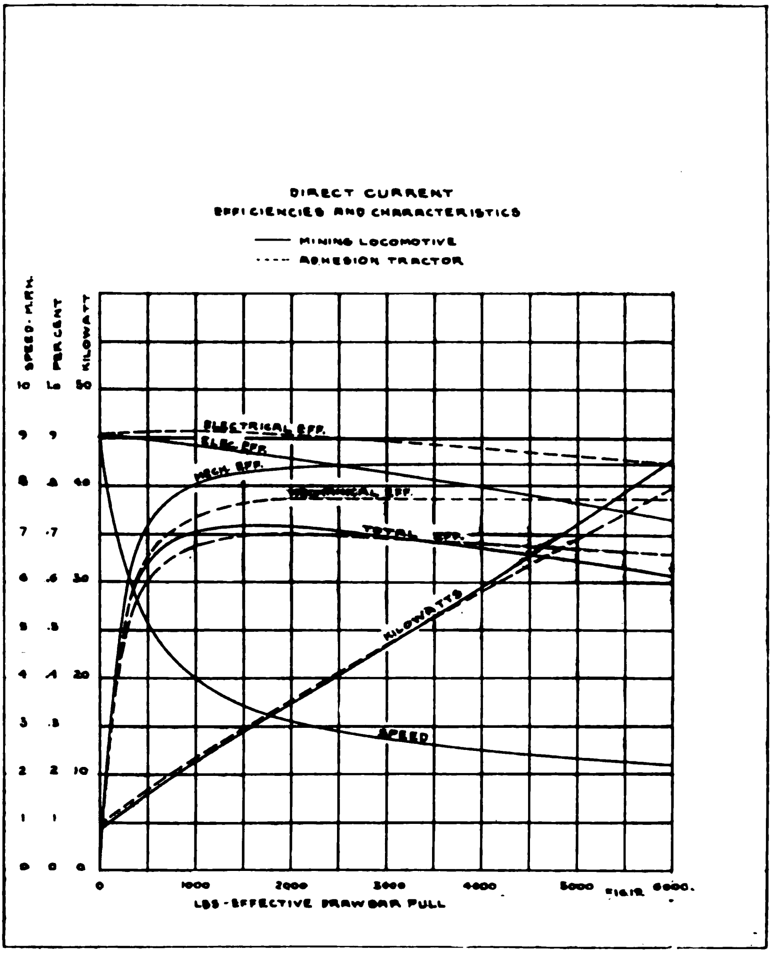

Fig. 19

(loaded) at the speed selected, will be 75 per cent. of the one-hour rating of the motor. The speed selected for both direct-current and alternating-current also corresponds to the speed recommended for two-boat tows. As already pointed out, this gives approximately the desired speeds for other tows.

Direct-current motors. The total efficiencies, kilowatt input at trolley, and speeds for the mining locomotive and tractor are given below. The efficiencies and inputs include all mechanical and electrical losses:

TABLE XVI

	Speed mi. per hr.	Mining Locomotive		Tractor	
		Per cent. efficiencies	Input kilowatts	Per cent. efficiencies	Input kilowatts
Effective pull,					
At 1000 lb.........	4.0	70.2	11.3	67.2	11.8
At 2000 lb.........	3.1	71.6	17.3	70.0	17.7
At 3000 lb.........	2.7	69.5	23.3	69.0	23.5

It will be noticed that there is comparatively little difference in the efficiencies of the two machines tested, notwithstanding the fact that, as previously stated, the mechanical losses of the tractor materially exceed those of the mining locomotive. This is due to the fact that the electrical losses of the two small motors used on the mining locomotive exceed the electrical losses in the single large motor used on the tractor; assuming in both cases that the motors are geared to obtain the speed which we have selected.

Improvements in design would make it possible for the mining locomotive to retain a larger part of its advantage, due to its less mechanical friction.

The relative efficiencies and characteristics of the two machines are illustrated in Fig. 19.

Alternating-current motor. By a similar process, the characteristic curves for single-phase, alternating-current operation have been deduced. In providing motors for the mining locomotive, we have assumed the same ratios between the efficiencies of two- and one-motor equipments as existed in case of direct-current. The following table shows the comparison of the two machines, including all mechanical and electrical losses:

TABLE XVII

	Speed mi. per hr.	Mining Locomotive		Tractor	
		Per cent. efficiencies	Input kilowatts	Per cent. efficiencies	Input kilowatts
Effective pull,					
At 1000 lb..... ..	4.3	66.8	13.0	64.5	13.4
At 2000 lb.........	2.9	68.4	17.0	67.0	17.3
At 3000 lb.........	2.3	67.2	21.2	66.5	21.5

The respective characteristics of the two machines are also shown in Fig. 20.

The average efficiency of the mining locomotive is about 1.5 per cent. higher than that of the tractor both with alternating-current and direct-current equipment and the average efficiency at the trolley is about 2.8 per cent. higher with direct-current than with alternating-current.

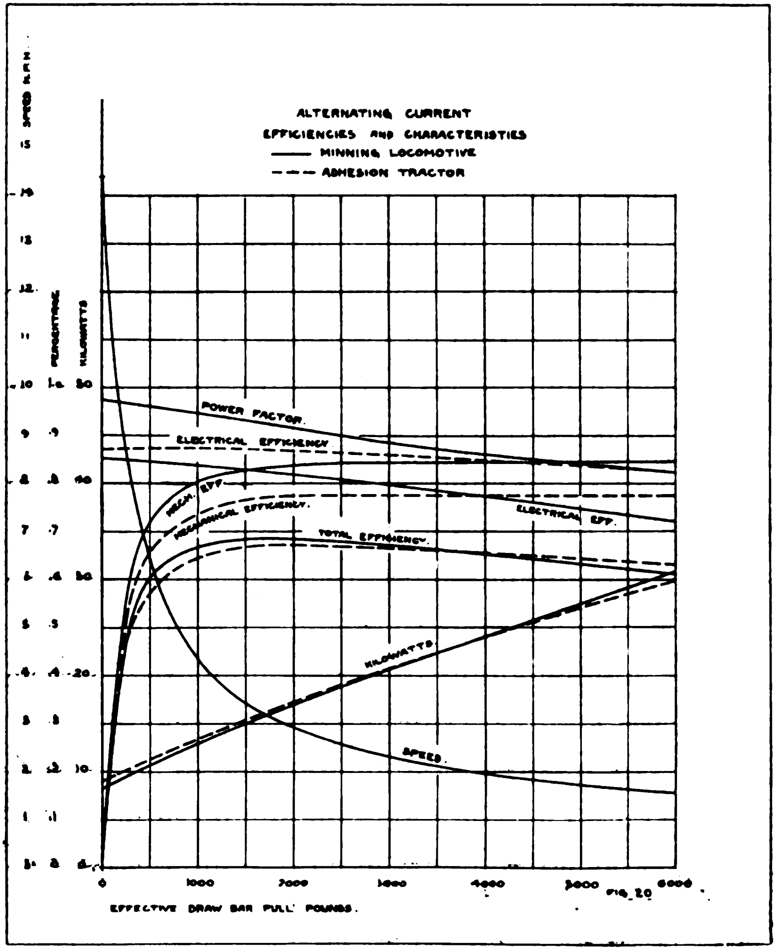

FIG. 20

In this case, as in the case of direct-current equipment, it is evident that the difference in efficiency of the mining locomotive and the tractor, and of alternating-current and direct-current equipment, are relatively unimportant as compared with other factors upon which the choice of one or the other as a system of electrical haulage must depend.

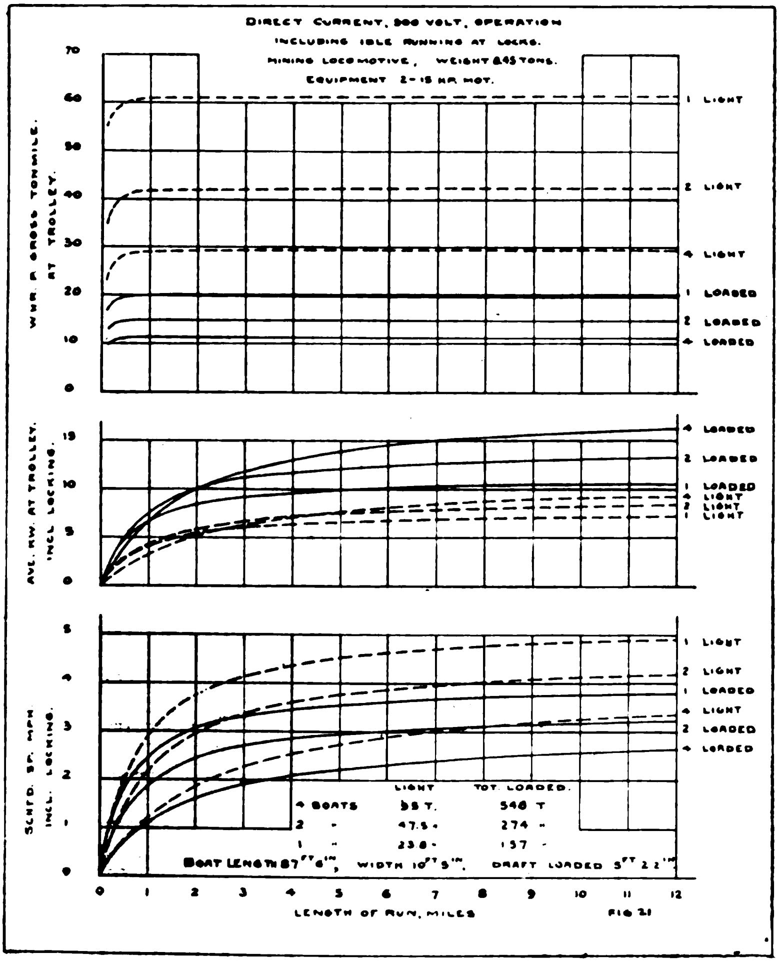

FIG. 21

Characteristic curves showing the average speed including locking for runs of different length, the average power required at the trolley, and the watt-hour per ton-mile for four-, two-, and one-boat tows for the mining locomotive and the tractor and for both alternating current and direct current are shown in Fig. 21, 22, 23, and 24.

The average length of run for the entire canal is 1.52 miles, and from calculations we have made it appears entirely practicable to use a run of this length as typical for the entire canal. Table XVIII shows the more important points brought out by these curves, on the basis that the locks are enlarged as necessary to accommodate two-boat tows.

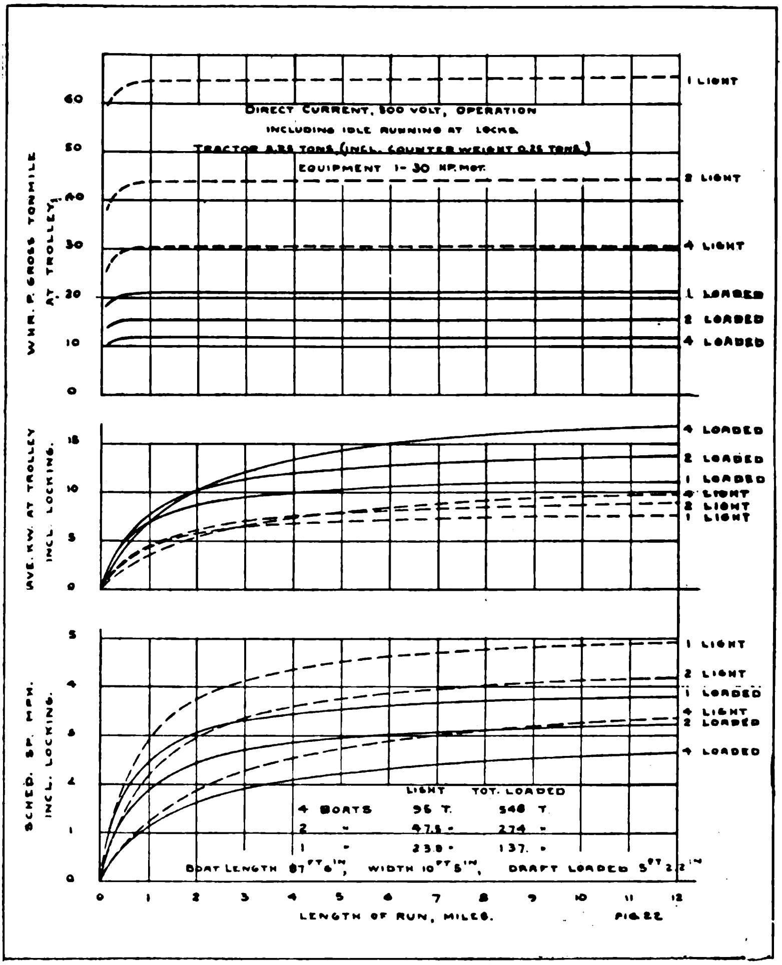

FIG. 22

TABLE XVIII

Speed, Kilowatt Input, and Watt-Hours per Ton-Mile. Average Run 1.52 Miles —Two-Boat Locks. Time Locking: 4 Boats 35 min.; 2 Boats 15 min.; 1 Boat 10 min.

	Speed		Mining Locomotive		Tractor	
	Maximum speed mi. per hr.	Average speed including locking mi. per hr.	Average input at trolley kilowatts	Watt-hours per ton-mile	Average input at trolley kilowatts	Watt-hours per ton-mile
Direct current.						
4 boats loaded....	3.00	1.40	8.7	11.3	8.8	12.0
4 boats empty....	4.00	1.60	4.3	29.2	4.6	30.3
2 boats loaded....	3.45	2.22	9.1	14.8	9.3	15.5
2 boats empty....	4.57	2.65	5.2	41.9	5.4	44.0
1 boat loaded.....	4.00	2.81	7.7	20.0	8.0	21.0
1 boat empty.....	5.30	3.42	4.9	61.0	5.2	64.5
Alternating current						
4 boats loaded....	2.88	1.37	8.1	11.0	8.2	11.1
4 boats empty....	4.13	1.59	5.0	33.5	5.3	34.8
2 boats loaded....	3.45	2.22	9.6	15.5	9.9	16.0
2 boats empty....	4.98	2.78	6.6	50.8	6.8	53.0
1 boat loaded.....	4.19	2.90	9.0	22.6	9.4	23.3
1 boat empty.....	6.00	3.67	6.7	77.0	6.9	80.8

TABLE XIX

Watt Hours per Ton Mile at Power House
(Average Freight Haul 55.6 Miles)

	Direct Current		Alternating Current	
Ton—2000 lb.	Mining locomotive	Tractor	Mining locomotive	Tractor
Watt-hours per total ton-mile				
Four-boat tows..................	24.6	24.8	22.6	23.0
Two-boat tows..................	30.9	32.5	32.5	33.8
One-boat tows..................	42.8	45.3	48.3	50.2
Watt-hours per freight ton-mile				
Four-boat tows..................	33.9	37.2	32.5	33.1
Two-boat tows..................	44.5	49.7	46.7	48.6
One-boat tows..................	61.5	69.0	69.5	72.2

For the conditions existing on the Lehigh and Delaware Canals, it is estimated that the efficiency of a system of electric power transmission and conversion supplying direct current to motors will approximate 70 per cent. from bus-bars at power house to motor terminals. If alternating-current motors be used the calculated corresponding efficiency is 75 per cent. Based upon these efficiencies and the traffic conditions as existing on the Lehigh and Delaware canals, the watt-hours required

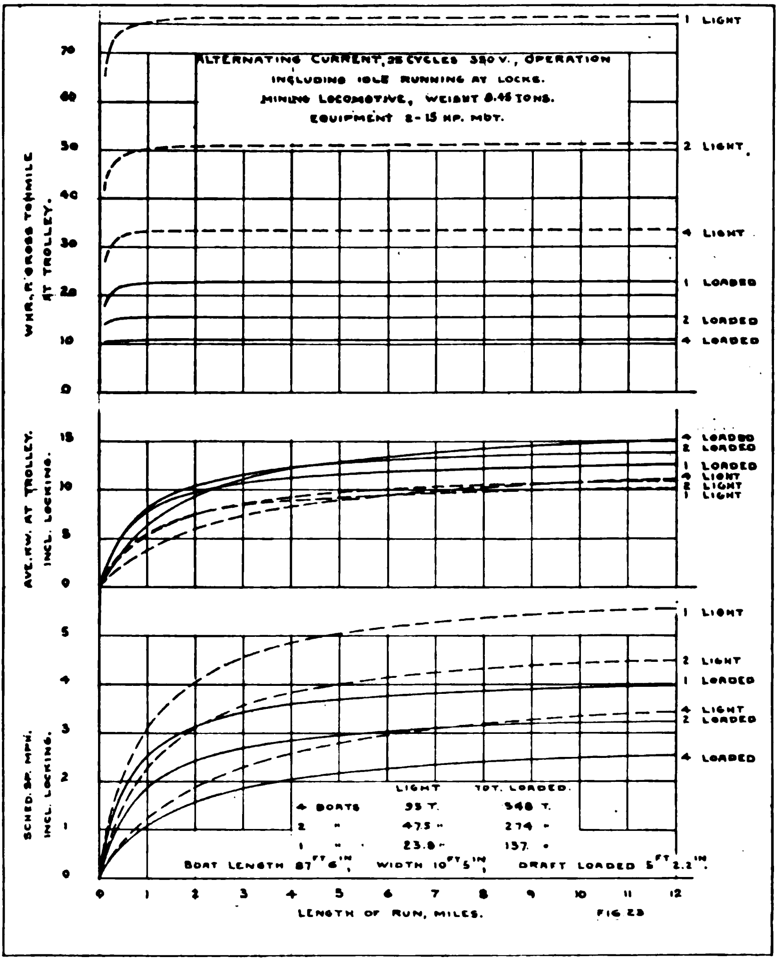

FIG. 23

at the power house per total ton-mile and per ton-mile of freight handled are given in Table XIX.

It should be noted that the calculated power for canal transportation, as set forth in the above table, applies only to the

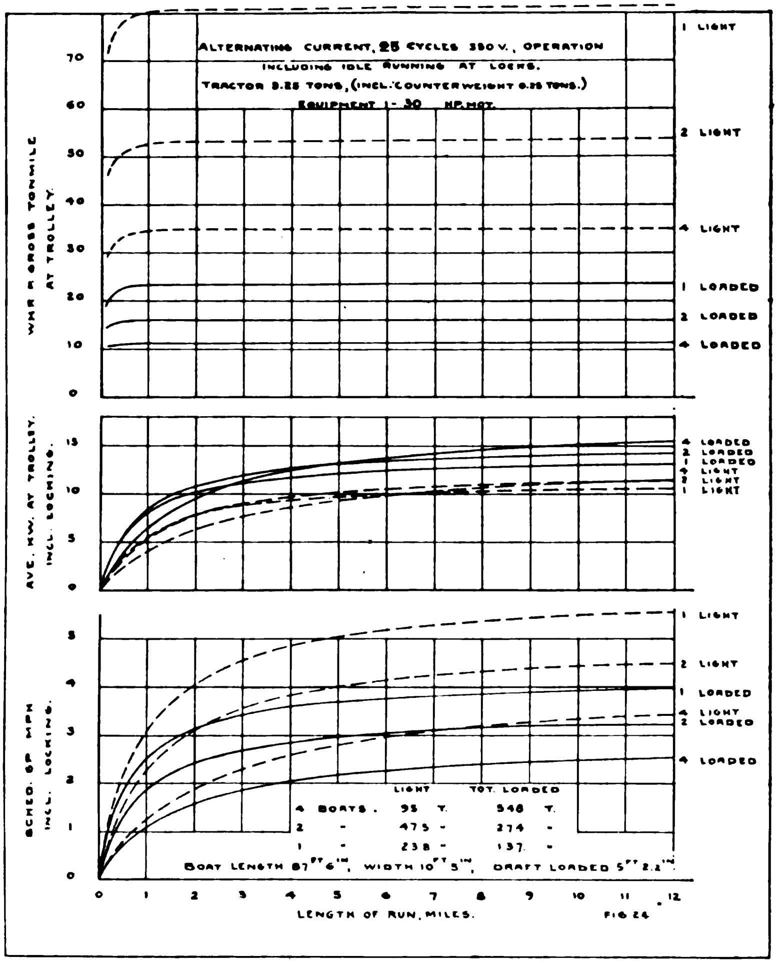

FIG. 24

especial conditions imposed by the physical limitations of these particular canals and by the speeds for loaded and for light boats which we have selected as most suitable for their operation.

A paper presented at a meeting of the Philadelphia Section of the American Institute of Electrical Engineers, Philadelphia, Pa., February, 10, 1908.

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(*Subject to final revision for the Transactions.*)

AN IMPERFECTION IN THE USUAL STATEMENT OF THE FUNDAMENTAL LAW OF ELECTROMAGNETIC INDUCTION†

BY CARL HERING

The fundamental law of electromagnetic induction, which is the basis of all our present mechanical generators of electric currents, is, in general, stated in two different ways. Faraday's statement is to the effect that if a conductor cuts magnetic lines of force, an electromotive force is generated. This simple statement, however, has been changed by later authorities, who define the same law by saying in effect that when the amount of flux enclosed by an electric circuit is changed, an electromotive force is induced. This is the more usual form taught to-day and recopied in most text-books in preference to Faraday's statement of it.

Maxwell in his classic treatise, Sec. 531, Vol. II, states the law in these words:

> The whole of these phenomena may be summed up in one law. When the number of lines of magnetic induction which pass through the secondary circuit* in the positive direction is altered, an electromotive

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†The object of this note is to point out that the usual and well-known statement of the fundamental law of the induction of currents by magnetic flux, is not correct as a universal law, and requires to be modified; when, applied as it is usually stated, it sometimes gives entirely erroneous results, although it is correct under the usual conditions. An essential qualification has apparently been overlooked. The proof is given by a simple experiment. The possibility of linking or unlinking an uninterrupted electric circuit with a magnetic circuit, without producing any induction, is shown. It leads to a clearer conception of induction and to a new form of continuous current generator.

* He had just previously shown that a magnet and a primary circuit are here equivalent.

force acts round the circuit, which is measured by the rate of decrease of the magnetic induction through the circuit.

Another high authority, Professor J. J. Thomson, in his excellent and more modern treatise (Elements of Electricity and Magnetism, Sec. 229, p. 388) states the law in these words:

> Whenever the number of tubes of magnetic induction passing through a circuit is changing, there is an e.m.f. acting round the circuit equal to the rate of diminution in the number of tubes of magnetic induction which pass through the circuit.

Other writers merely used different expressions to the same effect. One well-known form of expressing this law, is to consider the magnetic circuit and the electric circuit to be like two links of a chain: then, during the process of linking them together, an electromotive force is induced in one direction; when unlinking them, an exactly equal electromotive force is induced in the other direction.

The well known natural consequence of this law, when stated as it usually is, is that the same flux cannot be linked and unlinked repeatedly by the same closed circuit without generating alternating electromotive forces, hence the commutator of direct-current machines, and the inoperativeness of many suggested unipolar machines. Although not stated directly it is presumably understood that the electric circuit is not opened; the magnetic circuit unfortunately cannot be opened as there is no good magnetic insulator known.

Innumerable methods have been suggested, and doubtless many have been actually tried, to obviate, overcome, or neutralize this reverse electromotive force so as to produce direct currents without the necessity of commutation, but they have all failed except the Faraday unipolar dynamo, which has apparently not come into use for the usual voltages. According to this law, as it is usually stated, the former have failed because of this reverse electromotive force. It is now believed to be generally accepted and taught that this law is universal, and the attempts to evade it have lessened.

Recent investigations made by the writer and followed by experimental demonstrations, have, however, shown that the usual statement of this important law is imperfect, and that it requires to be modified in order to become universal. Probably others besides the writer have been misled by accepting this law as usually stated to be correct and universal. It will be shown below that it is quite simple to produce linkages or unlinkages, or to change or reverse the same flux enclosed by the same continuously closed circuit, without producing any electromotive forces whatsoever. It is true that the law as usually stated, seems to apply correctly to all the usual methods of producing electromagnetic induction at the present time; but it will be shown that, taken literally as usually stated, it is quite incorrect under certain other conditions, giving entirely erroneous results and must therefore be modified in order to become universal, or else be limited to those conditions to which it does apply, in which case it cannot of course be called universal.

It is not denied here that Maxwell himself may have elsewhere described these limiting conditions, or may have elsewhere described induction under those unusual conditions. If so, his followers should have made similar explanations in teaching his version of the law, so that students should not be misled.

Some time ago the writer suggested a so-called unipolar machine (that is, one having unipolar instead of bipolar induction) based on an apparently new phenomenon,* which would be operative if this law, as it is usually defined, is correct; but it was thought by him and also by Dr. E. F. Northrup, that it would fail, notwithstanding this law. It was concluded that it was not the change of flux in a circuit, or the linkages of the *circuit* with the flux, which determined the induction, but that it was essential that the *material* itself which composed the conductor must actually cut or move through the flux, (or the flux move across it). It was thought that Faraday's way of stating the law was nearer correct than the supposedly improved and more general form of his successors.

The following simple experiment was devised by the writer to investigate the correctness of these conclusions.

A loop *L*, Fig. 1, was formed of two flexible strips whose ends pressed together at the joint *J*, and the circuit of the loop was closed through a galvanometer *G*. On moving this loop over one leg of a U-shaped permanent magnet *N S* from the dotted position to that shown in full, an electromotive force was induced, as is well understood. The magnetic flux has thereby been linked with the electric circuit; the flux enclosed by the circuit has been increased from zero to the maximum; or to use Faraday's terms, the lines of force in the air from one pole to the other, have been cut by the conductor. So far, the law as it is stated is correct.

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* "A Practical Limitation of Resistance Furnaces; the 'Pinch' Phenomenon." By Carl Hering. Trans. Amer. Electrochemical Soc., Vol. XI, 1907, p. 329. Also "Some Newly Observed Manifestations of Forces in the Interior of an Electric Conductor". By Edwin F. Northrup. Physical Rev., Vol. XXIV, No. 6, June 1907, p. 474.

If this loop be now moved as shown in Fig. 2 from the dotted position to the one shown in full, by passing the leg of the magnet through the joint *J* of the loop, but ***without opening the circuit***, the flux and the circuit will be unlinked again; that is, the flux enclosed by the circuit will again be reduced from a maximum to zero, and the circuit will have cut the same lines of force in the opposite direction, as it is well known that all the flux of this magnet passes through its interior.

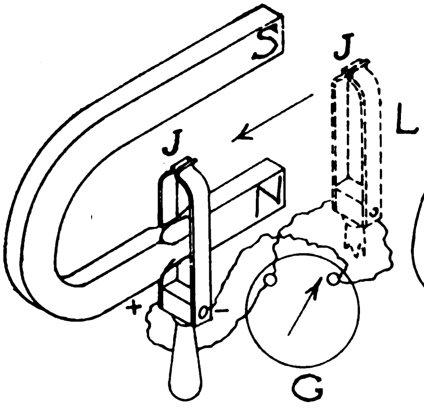

Fig. 1

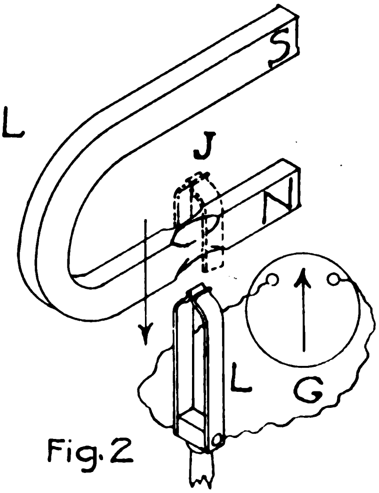

Fig. 2

According to the law of induction as quoted above from Maxwell, or J. J. Thomson, and as almost universally accepted, there ought then to be an electromotive force induced which is opposite and exactly equal to that induced by the first movement shown in Fig. 1, which will be seen by reading the law as there stated, on to this experiment. The fact is, however, quite the contrary; *there is absolutely no electromotive force induced by this unlinking*. Moreover, the same circuit is then free from flux and can be linked again repeatedly in the same direction with the same flux as before; a rapid repetition of these two movements increased the deflection more than ten fold.

This is believed to be the first direct and simple experiment which proves conclusively that it is possible to link and unlink a flux with a closed electric circuit without any induction, thereby showing that the usual statement of Maxwell's version of the law should either be restricted to certain conditions, or be modified so as to become universal without the necessity of more or less complicated interpretations.

It is also believed to be the first experiment which shows that in applying Faraday's version of the law it is important to make a distinction, heretofore apparently not recognized, between the conductor itself and the mere current path or circuit, when induction is concerned.

Through the kindness of the Leeds & Northrup Co., the experiments were made in their well equipped laboratory and were confirmed by my friend, Dr. Northrup himself. With his usual care and precision he even amalgamated the contact at the joint *J* and at the surface of the steel magnet where the loop passes over it, so as to be absolutely sure that the total absence of a deflection was not due to a possible open circuit. The magnet was ground down to a knife edge on each side, forming a lozenge shaped cross-section at the place where the passage of the strips over the magnet took place.

To be still further assured that there was no open circuit during this unlinking, the writer modified the test by passing a constant current from a battery, through the circuit during both the linking in Fig. 1 and the unlinking in Fig. 2. The linking was then found to increase (or diminish) the deflection, but during the unlinking the deflection remained constant; had the circuit been opened during the unlinking, the deflection would have indicated it at once by falling as was shown by unlinking the loop over part of the magnet which had been painted. The galvanometer used was one that was suitably adopted for the necessarily low electromotive force and low resistance; its sensibility was 38 megohms, and its resistance was 140 ohms; the deflections were therefore very decided and reliable; the test was repeated numerous times, thus leaving no doubt as to the correctness of the results.

This experiment, therefore, teaches us that it is *not* the linking and unlinking of the magnetic and the closed electric circuits, and it is *not* the changing of the amount of flux enclosed in the closed circuit, which is the prime cause of the induction, as it proves that such unlinking or changing of the flux can take place *without* any induction whatsoever. The cause of the induction must therefore reside elsewhere.

It appears from this experiment that it is the *material of the conductor of the current*, and not merely the circuit itself, which must actually move across the flux (or the flux move across it) in order to cause induction. In the experiment, the circuit itself did move across the flux during the operation of unlinking because the unlinking of the two circuits was effected completely; both circuits having remained unbroken, it of course follows that they must necessarily have cut each other. The only part of the conductor which did not move relatively to the flux during the unlinking, is that part of the material composing the magnet which is embraced between the two contacts; the circuit here did cut through the flux, but the material of the moving conductor did not; this appears to be the only difference, hence it seems essential that this feature should now be embodied in the statement of a law which is intended to be universal.

As the term " conductor " implies the material thing itself, when distinguished from a theoretical line representing the closed circuit or current path, it might suffice to emphasize the condition that the conductor itself must cut across the flux, in stating the law in Faraday's way.

If that later statement of the law which is in terms of the change of flux included in a circuit, is still to be used as a universal law, some limiting clause will now have to be added to cover the case shown in this experiment. A " change of flux " is not sufficiently definite, the change must occur in a certain way in order to be effective. But in view of the fact that this experiment seems to show that the real or prime cause of the induction does not reside in the "change of flux" at all as is usually believed it would seem to the writer to be preferable not to continue to define induction in those terms at all, but to use other terms which more clearly embody what seems to be the real prime cause. In other words, it seems to the writer to be better now to go back to Faraday's original definition in terms of cutting the magnetic lines of force, than to use the one of Maxwell which is in terms of the change of flux.

Maxwell and his followers, in generalizing this law, seem to have gone too far, because, *as it is quoted above*, it includes in its scope a case in which it gives entirely erroneous results. His predecessor, Faraday, was nearer correct when he described the induction to be due to "cutting the lines of force." Even Faraday's definition as incorrectly interpreted by others who used the word " circuit " instead of " conductor " (Faraday apparently did not do so himself), should now be modified or qualified to the effect that the conductor itself, and not merely the circuit must do the actual cutting.

As to stating the law in terms of the linking and unlinking of the two closed circuits, it seems difficult to so qualify it now as to limit it to the specific and probably the only kind of linking and unlinking which *is* effective, and exclude the kinds which are ineffective. This is unfortunate as this idea of linkages formerly afforded a very convenient and useful conception of the nature of induction.

In Faraday's original experiment with a revolving bar magnet and a loop running from one pole to the middle of the magnet, this same phenomenon occurs. The *circuit* itself cuts the flux in the interior of his bar magnet, as Faraday himself says; but he did not notice that the corresponding part of the conductor itself, does not; if it had, he would not have obtained the results described. He thought the lines of force remained stationary in space while the magnet revolved. The important distinction between the material of the conductor, and the circuit itself, when induction takes place, seems therefore to have been overlooked by him, notwithstanding that in stating the law he used the term conductor and not circuit.

The writer desires to repeat that the usual statements of this law in terms of the change of flux seem to apply correctly to all the ordinary cases occurring in our present practice, and that the limitation now pointed out therefore does not alter in anyway the former applications of that law to those cases. But as those statements of the law are directly contradicted by the present unusual case, the law as usually stated is not universal; and it misleads as it did the author, by making it appear that certain actions will always take place, when as a fact they sometimes do not. These statements of the law are unsatisfactory also in that they intimate that the *prime cause* of the induction resides in the changing of the flux embraced by a circuit, when it seems now as though it resides in the actual passage of the flux across the material conductor itself, and that it is located there and is not a property of the circuit as a whole.

It may be claimed that this experiment does not show an "error" in the usual statement of the law, and that it might equally well be claimed that Ohm's law is in error because counter electromotive forces, inductances, capacities, skin effects, Hall effects, etc., in the circuit, modify the results obtained by it.

But the latter does not seem to be a parallel case; Ohm's law treats of the relations of three quantities, and if there are more than three, the excess must either be eliminated or expressed in terms of one or more of the three, before Ohm's law can apply as such, and it is then correctly stated. The law of induction, however, as usually stated, actually gives totally erroneous results in some cases, as will be seen by reading Maxwell's or J. J. Thomson's statement of the law, on this experiment. This law treats of three things (1) a circuit, (2) an alteration of the magnetic flux enclosed by it, and (3) an electromotive force produced by such an alteration; it treats of nothing else; and if the results specified by this law *as usually stated* are not obtained or are not correct, when no additional quantities are introduced it seems to the writer to be justifiable to say that the statement of the law is faulty and is actually in error when applied to those cases. Aside from this, this law seems to give an erroneous conception of the real cause of the phenomenon.

The present experiment is also thought to be of considerable interest in connection with the long discussion of many years duration, as to which of the two so-called theories was the better one to teach and use, the one of Faraday based on the "cutting of lines of force," or the one of Maxwell based on the "change of flux enclosed by a circuit." It seems to show that after all, Faraday's original statement which was based on experiment, was more universal than Maxwell's, which latter appears to have been a mathematical generalization.

Another feature of interest of this experiment is that it seems to indicate that the induction is localized, and takes place only in that part of the conductor which passes through the flux, and not in any other.*

There seems to be no reason why the present experiment should not give the same results if a piece of copper were introduced in or around that part of the magnet over which the loop slides; and that this piece of copper might be insulated from the magnet, in which case the loop may have more than one turn, if there are a corresponding number of insulated copper pieces. This was not tried.

Fig. 3 was suggested by Dr. Northrup to show how the experiment might be repeated without involving any iron or steel in the phenomenon. Two solenoids are used instead of the permanent magnet, and one of them is surrounded by a copper ring *C* over which the joint of the loop passes.

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*The so-called "Dead Wire on Gramme Armatures." By Carl Hering. The Electrician and Electrical Engineer. May, 1887, p 171.

A continuous current generator without a commutator may be constructed in accordance with the results taught us by this experiment. Fig. 4 shows diagrammatically a simple way in which this might be done for demonstration purposes, although not for a commercial machine. The diagram explains itself; a number of magnets are placed symmetrically around a center and a single circuit of as many loops as desired may be made to cut all of the fields in such a way as shown, that the electromotive forces induced in the several loops are added in series. Doubtless the machine would operate as a motor also. Unfortunately, however, such a machine seems to have the same limitations as the usual unipolar ones, in that two sliding contacts moving at high speed, are required for each element of the circuit which passes through the flux.

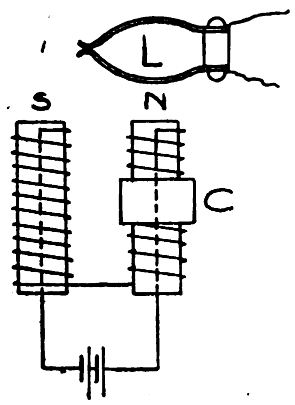

Fig.3.

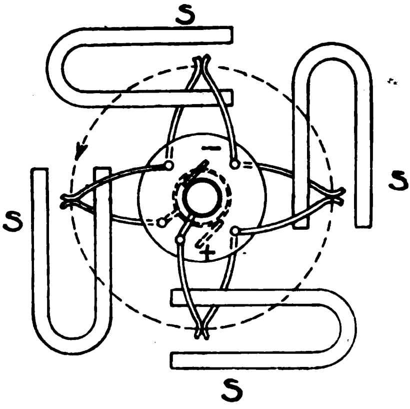

Fig. 4.

In accordance with general laws, the converse of the phenomenon shown by this experiment should also be true, namely, that when applied to motors it is the material of the conductor itself, and not merely the current or the circuit, which is caused to move through the magnetic field; in other words the electromagnetic forces act on the conductor and not on the circuit or on the current.

In this form it has long been known. For instance in a Faraday disc unipolar machine when used as a motor, it is not the circuit nor the current which is rotated through the disc, but it is the disc itself, on which the forces act. In other words, it is not necessary to make the disc of separate radial wires insulated from each other, in order to confine the currents to radial paths. On the other hand, however, there is the Hall effect in which it is the circuit, that is, the path of the current, which is deflected in a large conductor, when the conductor is not permitted to move.

The phenomenon illustrated by the present experiment may perhaps explain the reasons for the well known action of a magnet in "blowing out" an arc. The magnet appears to exert its forces on the material forming the conductor, namely on the ionized conducting gases which carry the current, and not on the current itself; the current follows the moving conductor, instead of the conductor following the moving current path.

The present experiment naturally gives rise again to the interesting question of what forces exist, if any, which oppose the change of the path or circuit of a current which is flowing through a large moving conductor. If for instance, a current is passed from one side of a rapidly running river to the other through the water, is the path different from what it would be if the water were at rest? A study of this question may not lead to any practical results, but it may nevertheless be of interest and perhaps be instructive in aiding us to obtain a better conception of the true nature of conduction.

I desire to repeat here that the error pointed out by this note does not affect the applications of this law to the usual electromagnetic machinery and apparatus of the present, and is therefore of no importance in that sense; the importance of it lies in showing that the law as usually stated, and when applied directly as stated, gives entirely incorrect results under certain conditions differing from the general ones; also that it misleads; and that it is not universal; to become universal it should be modified instead of having to resort to what is little short of mathematical juggling to make it fit this case. The importance of this experiment is perhaps, that it seems to give us a clearer conception of the real phenomenon of electromagnetic induction, its probable cause and its location; it shows conclusively that the change of flux enclosed in a circuit cannot by itself be the prime cause of induction; unless a further essential condition be fulfilled, such a change of flux fails to induce an electromotive force.

Attention might here be called to a very early experiment of

Faraday published in 1831, which has apparently been overlooked by the followers of Maxwell; it is described in his Researches, Paragraph 101. Maxwell's statement of the law also fails to apply to this, unless modified, as the flux included in the circuit always remains the same even though there is an electromotive force induced in that circuit. It also requires some interpreting of the law to make it apply to the case of the Faraday unipolar machine, a fact which many students and their teachers have experienced.

The writer desires it to be clearly understood that he does not deny that the usual statement of the law involving the change of flux idea, might be made to cover this experiment by adding various conditions or restrictions, or by various more or less complicated interpretations now suggested by the results of the experiment itself, and it might be claimed that there is then no error in it as a universal law. The writer's comments were intended to apply not to such modifications or interpretations of that law, but to the law as it was published and republished, and as it is and has been taught to students. In that form a student would certainly not have predicted the results of this experiment correctly by it, for in that form it directly contradicts the results. Faraday's statement of the law, on the other hand, when stress is laid on the distinction between the conductor and the mere circuit, predicts the correct result directly and without interpretations or other conditions. But aside from the question of whether or not it can be called an actual error, the more important question is now, whether Faraday's version is not simpler, more universal, safer, more direct, and much easier for students to learn and comprehend than Maxwell's.

A paper to be presented at the 227th meeting of the American Institute of Electrical Engineers, New York, April 10, 1908.

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(*Subject to final revision for the Transactions.*)

THE ENGINEER'S ACTIVITY IN PUBLIC AFFAIRS—PUBLIC UTILITY COMMISSIONS AND FRANCHISE VALUATIONS

BY HENRY FLOY

Americans are, in a mild way, extremists. They start for the goal with such impetuosity and zeal that they often overrun the mark and then have to return to it. This is what is now happening to public opinion with reference to the corporations. No language is strong enough to express the public condemnation of corporate mismanagement, usurpation of power, and larceny of funds which have recently been committed. On the other hand, all public utility corporations are not bad; and the engineer, knowing this, should be among the first to oppose the illogical, unreasonable condemnation of our present commercial system which causes a loss of the confidence on which our business relations are founded, and results in weakening the foundations of our whole economic structure.

As President Woodrow Wilson has truly said:

> Scathing indictments of our present industrial and political conditions are what we are suffering from at the present moment and they are to be offset, not by other scathing indictments, but by a very calm and self-possessed examination of actual conditions of things. What we need at present is not heat but light.

As a matter of fact, public sentiment is now undergoing a reaction; the American sense of right and fair-play is winning. The pendulum has reached its extreme position and is starting to swing back. The excesses in which the public mind has been indulging, indicated by the cry for indiscriminate municipal ownership, governmental and socialistic management, are being replaced by a more sane demand for control and regulation.

It is beginning to be recognized that a corporation must not only serve the public but also the stockholders; that the public cannot be served by corporations unless the stockholders receive a return on their investment concomitant with the risk; that capital cannot be compelled to invest on terms unacceptable to it. This change of sentiment, however, does not mean, as is clearly evident to the well-informed engineer, that the public will ever again return to its former *laissez faire* policy toward corporations.

Just at this time, during this important readjustment of relations between the public and the corporations, it is proper, yes necessary, that the engineer should pause to consider the lessons to be learned from recent experience, formulate his opinions for the future, and thus be the better prepared to coöperate in ending the present feeling of unrest and antagonism and share in the successes of the new advance which is sure to begin soon. Although by education, training and experience the engineer is presumably well-balanced and not excitable, he may nevertheless be influenced by popular sentiment or the demands of the corporations or financiers. During this transition stage especially, when the demands upon his time are restricted, he should take the opportunity to verify his opinions, reestablish his conclusions, and calmly determine his future line of action.

With these thoughts in mind, this paper has been prepared to serve as an introduction to a discussion which it is hoped will help to a crystallization and unification of the ideas of the members of the Institute on but three, of many similar important non-technical questions now demanding the serious consideration of broad-gauge engineers; namely, activity of engineers in public affairs, public utility commissions, and franchise valuations. The author's comments must not be taken as an attempt wholly to cover the subjects touched upon, or to reach conclusions which may not require modification, as the questions considered could very properly occupy the attention of the Institute at more than one session and they present viewpoints almost as diverse as is its membership.

Activity of Engineers. Considering the importance of the real work done by the engineer in the recent commercial development of this country, the comparatively unimportant public part taken by him is rather striking. His inconspicuousness can probably be accounted for by

(a) His keen interest in the purely scientific aspect of the enterprises with which he is connected; with him a "blunder is a crime". The engineer, like the teacher or the ecclesiastic, has a certain love for his profession which absorbs and recompenses him, in a degree, independently of monetary reward or fame.

(b) His natural hesitancy in pressing his own claims to recognition. Most lawyers or politicians are ready speakers, used to argument, and therefore, by profession trained to make their own case a strong one.

(c) His lack, in the past, of a broad, general education, especially along the lines of history, political economy, and what Dr. Humphreys, of Stevens Institute, in a recent address, called "business engineering". A narrow, purely technical training does not conduce to a broad, liberal consideration of any subject.

(d) His too frequent inability to speak fluently in public. The engineer does much of his work individually, quietly, on paper, so that he often becomes embarrassed when called to express his opinion from the platform.

As a result of these limitations the engineer has hardly received the public recognition which would be expected. Perhaps the most striking recent illustration of this was in the appointments made to the two Public Utilities Commissions of the State of New York, which included fourteen high-class, well-paid officials. Of this number only one has had a technical training, although in the hands of these commissioners are placed, with almost despotic power, the affairs of large engineering enterprises in the State of New York, estimated to be valued at about $3,500,000,000. This exception is the more striking when it is considered that the same governor, in naming the Hepburn Commission to inquire into and report with recommendations as to the condition of banks, financial affairs, and their improvement, selected bankers; and, when a commission was named to consider and make recommendations with regard to the Torrens system of registration of land titles, the commission was almost entirely made up of men prominent in real estate matters. Mr. George W. Perkins, in a recent address, referring to a commission to have national supervision of railroads, said:

> It should be in the hands of experts. A railroad commission, for instance, should be composed of railroad men who can deal with the question arising in a practical way. This kind of expert, high-minded super-

> vision would not be opposed by the business interests of the country. What they dread is unintelligent, inexperienced administration.

Mr. Perkins but expresses the accepted opinion that experts are the proper parties to have supervision of matters in which they are specialists. Even the New York State Court of Appeals, in a recent decision relating to the constitutionality of the statute creating a commission to determine rates, says :

> That the most appropriate method (speaking from a practical, not necessarily constitutional point of view) is the creation of a commission or body of experts to determine the particular rates has been said several times in the opinions rendered by the Supreme Court of the United States in the various railroad commission cases and in those of State courts.

It is well known that the House of Lords in England, when it sits as a Court of Appeals, has the cases submitted to its law members, which would seem to be the only rational practice. Contrary to such general belief, the opinion prevailing in selecting the New York State commissioners, as indicated by their appointment, was that if they possessed unquestioned integrity there existed no special reason for naming men experienced in handling engineering or transportation questions. This has resulted in the necessity of hiring engineering subordinates, which increases expenses and decreases direct responsibility, because the advice of more or less independent experts reporting on matters of detail is quite different in value from the advice given by a technical member of a board identified with its policy and responsible to the public for the discharge of his obligations. Hired experts can never be made to shoulder the responsibility for a decision rendered by a commission composed wholly of men untrained in public utility affairs and perhaps unable fully to appreciate the technical effect of their orders.

It is noteworthy that much of the work of the commissions is divided, one member investigating one question and a different member another. With two or three commissioners as engineers, the engineering questions would naturally devolve upon these members, and they could solve them much more quickly and unequivocally than could politicians, lawyers, or business men unacquainted with even the terms involved, to say nothing of understanding the practical conditions under which a lighting corporation, or steam or electric railway company, must operate. A perusal of the minutes of the hearings held before state commissions will convince any unprejudiced person that a disproportionately large amount of evidence and testimony is submitted, with consequent unnecessary financial expense and consumption of time for the purpose of explaining terms, apparatus, and methods of operation and expenditure to commissioners who, in general, should be acquainted with the matters being considered. This and similar evidence surely indicates that the efficiency of the commissions is largely reduced by lack of proper make-up. For this condition of affairs the engineers themselves are partly to blame.

The antiquated notion that every engineering expert is unable to appreciate any question outside of its purely technical significance is disproved by the fact that the success of the engineer is often based on a liberal education with wide experience, giving him a capacity for proper consideration not only of technical but also of commercial and political factors that enter engineering undertakings, and also by the fact that the administrative and executive staffs of many of our largest and progressive organizations are being constantly recruited from the engineering profession. To become president of the Pennsylvania Railroad, judging from precedent, one must have, in addition to other qualifications, both a technical education and practical experience in engineering work.

By reason of the work and position of the engineer in the business and technical world, is it not reasonable to expect that at least one-half of the membership of the public utility commissions, being named from time to time throughout the country, should be composed of experienced, broad-gauge engineers. I venture to prophesy that as public service commissions become more common, they will be constituted more and more of men drawn from the ranks of those having practical experience with the work to be undertaken. In fact, I can conceive of no more independent, dignified, influential or beneficent occupation in which an engineer can be engaged, and I believe the honor of the position will ultimately attract to it our most capable men whom now the monetary inducement will not interest. The present inertness of the profession in these matters is noticeable. Last spring the writer personally sought to have the officials of some of our engineering clubs and societies develop sentiment looking to action on the part of these respective organizations toward obtaining the appointment of some men of engineering experience on the New York State commissions, but only one organization acted. The public utility corporations themselves, represented by a number of executive officers in conference, showed some interest in securing commissions capably constituted, but no definite results came from the conference. Even the labor unions have actively urged they be represented on the commissions, simply on grounds of self-interest, while the engineer, with especial qualifications for the work has too much pride to ask recognition, even with semi-altruistic motives. It is a hopeful sign that for the first time in its history the American Society of Civil Engineers recently memoralized Congress, urging legislation for the preservation of our forests, a precedent which might well be followed by the Institute.

The commercial importance of the engineer is steadily growing, and he should recognize the claims upon him to take part in public affairs and assume the responsibility more and more laid upon him, of leadership. His increasingly closer business relations with public matters and his reputation for integrity give his opinion and influence steadily greater weight in large affairs, which he should appreciate, accept, and respond to. While the engineer's work must always be professional, in a way judicial, and should always be accompanied by high moral sense, the successful engineer must nevertheless combine practical business qualifications with his scientific work. There can be no good engineer—in a broad sense—unless combined with his technical conclusions there is included such recognition of commercial conditions, as will thereby permit him to attain the worthy objects of his chosen profession with maximum efficiency.

Public utility commissions. The aggressive, almost insolent, and oftimes unfair attitude of some utility corporations has created an insistent demand for further and more direct control of operations than has been possible through the more usual form of legislative enactments. The American people are not, as a rule, over inquisitive as to somebody else's business, but when imposed upon, they do not hesitate to ascertain the why and wherefore. The result has been a publicity of corporation finances and affairs that now implies an obligation to afford the corporation legitimate protection in their business.

The necessity for regulation by the public arises, in the first place, because the exercise of franchise rights by certain corporations, while academically not exclusive, is nevertheless practically non-competitive; therefore, one of the ordinary checks arising through competition does not in such cases apply. Unlike the individual or ordinary business corporation, a public utilities corporation frequently cannot begin business without being organized under special and specific laws. Such corporations may be granted unusual franchises; for example, the right of eminent domain, and are recognized as existing for service to the public in a manner, and with privileges entirely unique and distinct from those of ordinary business undertakings, and are therefore acknowledgedly subject to special regulation and control. Even ordinary business corporations which have no special privileges granted, if uncontrolled, may, as the result of unusual commercial acumen linked with a large aggregation of capital—illustrated for example, in the case of the so-called " trusts "—create a wrong which organized society will very properly step in and limit, control, or prohibit. Business trusts are in effect monopolies, because competition as a practical matter is out of the question, and hence regulation in their cases is also essentially necessary. The underlying principle of monopolies, coöperation, is a legitimate product of our present civilization; it may be controlled but not prohibited.

In the second place, regulation of utility corporations competing for the same business is required from the very nature of the business itself. If they are allowed to compete fully and freely, experience indicates that they will ultimately engage in a war of annihilation, the expense of which is in the end borne by the security holder or the public. Up to a few years ago, political economists believed and argued that the only regulation required for all commercial operations was free and unrestricted competition:

> Because the experience of mankind had not developed essential monopolies, and it was believed that every problem which would arise would be solved by giving full play to the spirit of competition. * * *
>
> Whether that system of dealing with railroad corporations will succeed or not can be ascertained by viewing their history in the State of New York, and the experience which was had in this State, demonstrated that it did not work to the advantage of the public and that the evils connected with the system were simply enormous and unendurable. Competition could not exist upon railroads.*

Some years ago the state of Massachusetts appointed a Committee of Gas and Electricity, empowered to inquire into and revise rates charged, operating costs, capitalization, and to limit competition. Although this commission was looked upon as something of an experiment, the high quality of work accomplished by it has commanded the respect and approval not only of the public at large, but also of the corporations themselves, who, through its protection have been guarded against unfair and unnecessary competition.

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* F. W. Stevens address, A. I. E. E. dinner, 1908.

Encouraged by the good work accomplished through this commission, and other commissions having to do with railroads, etc., and supported by those who were opposed to municipal ownership but believed that the conduct of corporations should be regulated and controlled, there has developed within the last year or two a popular demand for other state commissions with large powers that could compel, particularly railroads and gas and electric corporations, to comply with their obligations and furnish reasonable service at fair prices. Without attempting to discuss whether regulation should properly be undertaken by the state or federal government, it would appear that if intelligent regulation of such corporations as railroads is to be obtained, it must be done at least in part by the nation rather than through each state attempting to pass its own laws, perhaps contradictory to those of an adjoining state in which the same railroad must operate. On the other hand, state or even municipal control of gas and electric corporations might seem both logical and legitimate, provided the personnel of the board of control is capable honest and unprejudiced. In fact, the corporations themselves, as a rule, welcome such regulation, as it will protect their properties from hostile and wasteful attacks, vicious competition, and unfair manipulation of its securities. Their objections are almost always based on either a fear of corrupt or dread of well-meaning, incompetent, and inexperienced men, as commissioners, or else that questions under consideration would be decided from the standpoint of the past rather than the present. For example, it would, of course, be unfair, to take advantage of the present investment of a corporation, of which the stockholders cannot unburden themselves, to make an unduly low price for its commodity. In each case the rate of return allowed a going corporation should be the same as that to a new corporation rendering the same service.

New York started in a mild way with several commissions for different purposes; but last year, under the leadership of Governor Hughes, the state passed laws substituting for the other commissions, two state commissions, one to have charge of all public utility corporations in Greater New York, and the other in the remainder of the state. To these two commissions were delegated almost unlimited authority, they having power to examine corporation affairs as completely as any board of directors, and to require changes in methods of operation and even reduction in prices charged for service.

Other states are following the precedent established by Massachusetts and New York. Wisconsin already has such a commission appointed under an act of the legislature, which is well worth perusal by any one desirous of learning the present-day radical trend of opinion. There is little doubt but that before long, *nolens volens*, most or all the states in the union will have commissions appointed to control and regulate at least the so-called public utility corporations. That such commissions have the right and power to determine rates, has been established in New York state by the courts, in the Saratoga case.

How, then, are these commissions to deal with the corporations in protecting the public, and at the same time give the investor every encouragement for profit, and the business no lack of opportunity? In this connection it is important that the engineer inform himself just what is the difference between operation, regulation, and confiscation.

With regard to operation, public utility commissions should restrict their action to general principles; they should not interfere with details, otherwise they will remove the present responsibilities from the shoulders of the directors to their own shoulders, restrict and hamper the efficiency of the organizations, still the incentive to work, and destroy the reasons for promotion of the employees—all of which will result in depreciating the service rendered the public and the financial standing of the corporations themselves. As has been well said:

> Regulation should stop where operation begins. Matters of business discretion should be left to the decision of those who are responsible for business results.*

If state regulation is to determine rates and limit the earnings upon investment, it may logically be asked, should the state not also include a guarantee of reasonable returns on the investment? If a corporation takes all the risks, it is logically entitled to all the profits. If the state prohibits anything more than a definite profit, may it not be morally bound to assure that profit? In fact, municipalities have been known to go a long way in this very direction by granting an exclusive franchise, which affords a monopoly and prevents competition.

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* Report, Committee Public Policy, N. E. L. A., 1907.

The principle of state control is not new, although its application has recently been greatly broadened. We have become so accustomed to considering liberty as unrestricted license for all, that the statement of Chairman Stevens of the New York State Commission, at the dinner of the American Institute of Electrical Engineers in February, that the public can demand and take from the individual, much less the corporation, anything " from his pocket book to his life inclusive ", was as startling as true. The only precedent to the taking, is the public necessity and the proper manner and remuneration. In theory, then, regulation is correct, if only the practical application to the concrete case were not so difficult.

Confiscation means the taking of property without allowing " fair return " thereon. Fair return is a smooth legal term which neither the courts nor anyone else has yet been able precisely to interpret. In the decision of the United States Circuit Court in the Columbus case, an unallowed demand for a reduction in electrical rates, a decision with which every engineer interested in public utilities should be acquainted, it was stated that, over and above legitimate operating expenses and depreciation charges;

> The owner of the property should be at least permitted to receive as his compensation for its use the legal amount of interest allowed by the state of Ohio.

The court then goes on to say:

> It may well be doubted whether the legal rate of interest is reasonable and just compensation to the owner of the property devoted to public use, etc. * * * It may well be doubted whether capital would at any time for this legal rate alone be willing to enter upon the rendition of public service of the kind performed by the complainant under these circumstances and conditions., etc.

Again in the famous case against the Consolidated Gas Company of New York, in which a reduction was sought from $1.00 to $0.80 per thousand feet of gas. The court has held that the owner is entitled to " a fair return upon the reasonable value of his property ", which is guaranteed to him by the famous fourteenth amendment to the Constitution.

Apparently, the existing state commissions realize the importance of a comprehensive, thoroughly considered, and reasonable line of action based on " well settled principles of public policy "; and they feel the necessity of proceeding cautiously in order to establish correct rulings and avoid the charge of confiscation.

But the radical feeling of the time, as well as some unexpected conclusions, are indicated by certain rulings of the several state commissions with regard to public utility corporations. These are worth considering as illustrating general conditions which the engineer must bear in mind when advising his client as to investments and earnings.

The commission of the second district of New York states that they have:

> Refused to consider the application of foreign (other than those incorporated under the laws of the state of New York) gas and electrical corporations to do business in this state, and have announced it as a rule that no application will be entertained.

The Wisconsin statutes provide that only corporations organized under the laws of that state shall receive franchises therein. It seems to me that this is a somewhat narrow policy which can not be long continued without modification.

The same New York State Commission has decided to accept as satisfactory, unsealed electric meters having not more than 4 per cent. of error, although requiring gas meters to be within 2 per cent. of correct, and sealed by a representative of the commission. It is doubtful whether the leniency of the commission toward electrical operating companies will compensate the manufacturing concerns for the odious comparison made of the electric meter with the much slandered gas meter.

The same commission announces unequivocally that it will require each corporation to maintain a depreciation fund which must be provided out of earnings. This is a very wise conclusion required by the statutes of some states, and a step which many corporations have failed to take, as they should have done for the protection of their security holders.

In the Lockport decision the New York State Commission established an important precedent; they allowed the consolidation of two competing companies, but prohibited, as prescribed by statute, the issuing of securities to an amount exceeding the total capitalization of the two old companies. They also prohibited any increase in the price of gas and electricity over the prices made by the respective companies during competition. Thus it appears, losses resulting from a war of extermination and the increased cost of consolidation cannot be met by the issuance of new securities, as formerly, which is from one standpoint radical and far-reaching. Again, the commission ruled that the low prices reached through competition should not be raised after consolidation, which, while protecting the public, possibly might tend towards bankruptcy for some consolidated companies.

As the result of its experience, the Massachusetts Gas and Electric Light Commission has recently reported that it finds the benefits of the consolidation of gas and electric companies in cities of considerable size do not compensate for the disadvantages to the public arising from such consolidations.

The engineer, of course, well knows that it costs more per unit to deliver gas or electricity to the small consumer than to the large consumer, yet the New York Commission of Gas and Electricity that went out of existence last July fixed a maximum kilowatt-hour charge to be made by the Rockland Light and Power Company in Orangetown. It has been shown that out of 112 customers served at a loss under the rate formerly charged, 75 would receive service under the new rate at a greater loss to the company; while out of 26 served at a profit, 19 must be served at an increased profit to the company in order to make good the losses increased by reduction of price to the 75 mentioned above. It is hardly necessary to say that the courts would not sustain this ruling, as was proved in the well-known Columbus case. The present commission has, by petition, taken under consideration an order to restore the old rates.

A consideration of the rulings of state commissions shows a tendency to place all corporations on the same footing as regards the returns to investors; that is, regardless of whether capital has been invested in a judicious and intelligent manner or in an inefficient way, the precedents established indicate that about the same profit will be allowed in either case. This, of course, does away with all incentive to improve the earnings by cutting down operating expenses, or to decrease the price, or introduce new apparatus or modern methods. It removes the stimulus heretofore existing with the individual, to make the very best showing possible, and hence is a reasonable, valid, and practical objection to control by commissions. One method of offsetting this very decided disadvantage has been evolved by the application of the London sliding scale, so-called because originating in London, England, and now in use in Boston. The principle is a profit-sharing one, in which the investors are entitled to a definite rate on their investment with a fixed price for their product to the consumer. Every decrease in price, as for example 5 cents per unit in the case of gas at Boston, entitles the investors to an increase of one per cent. in their rate of dividend. An objection to this plan is that while it may be perfectly fair for a term of years, improvements in methods of manufacturing may so largely reduce the manufacturing costs as to entitle the investors to abnormally large dividends, at which time a readjustment of the base for price of product and rate of dividend would result in seriously depreciating the securities held by the owner at the time of such adjustment. This London scale, however, is at present the best practical method evolved for automatically adjusting profits as between the public and the corporation.

Franchise valuations. In considering the expenses and profits of a public-service plant, the engineer must determine the proportion of earnings to be applied to taxes and dividends, the amount of both of which will usually be affected by the value of the company's franchise. At present the franchises of different corporations are variously valued at from less than nothing, or a liability, up to a $20,000,000 asset. Therefore, the competent public corporation engineer must understand what a franchise is, its dollars and cents value and its distinction from the good-will of a going organization, favorable contracts, or physical property.

A franchise is a license, granted by a state or municipality, recognizing the right of a public utility corporation to do certain business along prescribed lines. As the privileges and earning power of franchises vary, so their values vary. On one extreme it has been argued that because a franchise costs nothing, or is supposed to cost nothing, it should not be valued or capitalized by a corporation—the present New York statutes prohibit capitalization of franchises by new corporations—because then the public is forced to pay, by increased cost of service, the fixed charges on what they have themselves once owned and gratuitously bestowed. The corporation replies that its franchise is regularly and heavily taxed. If it has no value, it cannot fairly or logically be a subject for taxation; if it has value, it can and should be capitalized. The answer made to this is that the franchise tax is included among the items which go to make up the proper selling price of the corporation's product, and therefore is indirectly paid by the customer without in any way affecting the stockholders' investment or profit.

On the other hand, as the engineer well knows, franchises are frequently granted as a sort of bonus to induce capital to undertake, perhaps at a loss at the start, certain operations for the benefit of itself and the public. One purpose in accepting such obligations has been, not immediate return, but the profits to be gained in the future by the growth of the town or state and the consequent increase in revenue. As time goes on, the value of the franchise increases the same as real estate, or a desirable business location, and it would seem might be just as logically recognized as of value and capitalized.

Granted that certain franchises have become enormously valuable, corporations should not be disparaged on that account. If the public gave away something for nothing, they did so because they were unable to secure any price for it, or they failed to recognize its value and made a poor bargain, or their officers betrayed their trust. Under any of these suppositions the corporations may stand blameless, and are perfectly entitled to their franchises and the value of them. It is but a few years since it was impossible to interest capital in the construction of the New York City Subway; finally, privileges were offered as an inducement and the construction completed, which has proved a notable financial success. Should any one now claim that because the investors have profited largely the contract should be annulled? Yet a few weeks ago the startling doctrine was advanced by a public service commissioner that we of to-day are not bound by an agreement of yesterday, that:

> A common council or a legislature may barter away any present rights, yours or mine, for to-day. But the future is not theirs to give. They may not dispose of rights which belong to our children as much as to us, and to their children and their children's children after them. They may allow private development and management for the sake of immediate public advantage, any such investment must be scrupulously protected; but the franchise itself is something which may not be given away because it is not within the province of the Legislature to give away that which does not belong to the existing community.
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> A franchise granted by the legislature of fifty years ago belonged then to us of to-day quite as much, if not more, than to our grandfathers, who handed it over to some railroad in perpetuity. It belongs to us now, as it will belong to our grandchildren in their turn. The action of the legislature of two generations ago in giving away our birthright is not morally a binding contract upon us to-day when it comes in conflict with present or future public interests, and the vested rights of the private inheritors of that franchise will not stand when they come in conflict with the vested rights of the whole people of the State of New York.
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> This may not be 'good law' now, but I believe it will be in a very short time, for the public perception has grown very swiftly of late. And the courts of law are never very far behind public opinion. Some legal way will always be found sooner or later to do what is morally right.

If the commissioner is correct the engineer must know it, and figure a large annual depreciation on the value of franchises; he must ask when does the last generation's rights end and to-day's begin; on what day after granting does the legislature's perpetual grant cease, is it to-morrow or day-after-to-morrow, or next week, or when? Doubtless the commissioner is influenced by the trend of both public opinion and some recent court decisions emphasizing the right of public necessity as against individual or corporate welfare. Perhaps he is overwrought by intimate contact with the oppression resulting from certain grants; but, however rapidly we may have grown in socialistic doctrine, the engineer cannot agree that obligations can be broken simply because they are onerous. He recognizes that the franchise granted 50 years ago had neither the opportunities nor responsibilities of that same franchise to-day. New conditions beget new obligations, which the corporation must meet or the franchise may become valueless on its hands.

Aside from feeling or argument in the matter, the courts have held, and will doubtless always hold, unless it is expressly excepted, that a franchise is property and a more or less valuable asset. If, then, the franchise is property, what may be the value of the property? The present secretive, uncertain, inequitable, unscientific method of arriving at the value of each corporation's franchise, as practised by the State of New York, for example, is, to use the language of the courts themselves, " little more than a guess " and should be replaced by something simple, logical, uniform, and publicly determinable.

It may be right to prohibit the capitalization of future franchises beyond what they have legitimately cost, but the engineer interested in seeing a " square deal " should oppose any attempt to destroy by fiat legislation the value of franchises already established. In many cases there can be no objection to letting the corporations evaluate their own franchises, because the necessity of offering their product at a reasonable selling price on one hand, and, on the other hand, meeting the taxes that may be imposed by the public, will, in the end, generally establish a fair value for a given franchise. Where state commissions have been appointed with large powers to control and regulate public utility corporations, it will be necessary for them to determine a value for the franchises of the various companies under their supervision. Thus far, no logical or uniform method of evaluating franchises has been determined upon by tax assessors, the corporations themselves, the public utility commissions, or the courts.

The more common method of evaluating a franchise that has prevailed, especially among those interested in owning and selling corporation securities; namely, considering the franchise as worth the difference between the value of the physical property of a corporation, and the market value of its stock and bonds, can hardly be considered tenable, for the following reasons:

1. Because in such valuations is included not only the franchise value but also the worth of good-will, favorable contracts, business organization, etc.

2. Because the daily fluctuating price of stock and bonds due to general business conditions, market manipulations, or stock jobbery, make it, as a practical matter, extremely difficult to determine the fair market value of a corporation's outstanding stock and bonds.

3. Because the market value, even if correctly determined, does not indicate, in many cases, the real value of a corporation's stock and bonds. The market value of said securities often depends upon the success with which printer's ink and promoters' efforts have succeeded in impressing the mind of the public, which is generally ignorant, intentionally or carelessly, of actual operating and financial conditions.

The wide difference of opinion among the courts, and the general uncertainty as to the proper method of setting about fixing franchise valuations, is illustrated by the contradictory conclusions reached by the two different officers of the courts who have attempted to place a value on the franchises of the gas companies operating in New York City. The Master who conducted an exhaustive hearing in the matter decided that the franchises were worth $20,000,000. Judge Hough, of the United States Circuit Court, who reviewed the Master's report, concluded that the same franchises were worth $12,000,000. Certainly there should be some fair method evolved for more closely approximating the real value of a given franchise than the wide divergence indicated by these figures. The rule of law under which this country operates is not based on an opinion, guess, or the discretionary rule of an individual, even though clothed with governmental authority. The action of courts, assessors, or commissioners, must be restricted as far as possible to forming conclusions based on definite and fixed laws. It would seem as if the engineering profession, as a disinterested party, appreciating the necessity for and relation of a franchise to a corporation's business, might assist in evolving some method of fairly and logically fixing franchise valuations. The following is suggested with that thought in mind.

Starting with the premise that on one hand the investor in electric and gas utility securities has been demanding a return of from 9 per cent. to 15 per cent. on the actual investment, as shown by the testimony in the Consolidated Gas case from such witnesses as Messrs. Emerson McMillin, N. W. Halsey, Samuel R. Bertron, Allan B. Forbes, " bankers having much experience with gas properties in their investments ", and on the other hand that the courts, as indicated for example in the Consolidated Gas case and the Columbus decision, are inclined to base their decision of " fair return " upon the investment, upon the legal rate, which varies from 5 per cent. to 8 per cent. in different states, we have the extremes of earnings considered fair; namely, from 5 per cent. to 15 per cent. on the actual investment, depending upon location.

For purposes of discussion herein, consider a corporation operating in the state of New York, where the legal rate which, at least, will be allowed by the courts as a "fair return" is 6 per cent. In view of the fact that the capitalist has indicated that he will not be interested at 6 per cent., but that perhaps 9 per cent. would be attractive, are we not safe in assuming that with a New York corporation he would be content with 8 per cent. when he knows that his property will be defended from unfair taxes and competition through protection afforded by a state commission? The nature of the business, compared with other enterprises, is such that the return of 8 per cent. upon the investment actually made by a public utility corporation would not seem unreasonable. Now if the capitalist will accept 8 per cent., and the court will stand by the legal rate of 6 per cent., we have only to prove that the value of the franchise—which the courts have uniformly admitted should be considered as of value—is worth one-third the amount of the actual investment to secure an allowance of 6 per cent. on the whole, or 8 per cent. on the actual cash investment.

An examination of the values placed on many franchises in the past for purposes of taxation, capitalization, condemnation, or court decision, will indicate that perhaps an average valuation of the franchise in each case is not far from one-third of the actual replacement value of the corporations assets. This ratio, though somewhat arbitrarily assumed, would seem under present circumstances to be both a fair and reasonable one for existing franchises. If it is a middle ground on which the various conflicting interests could meet, we will have an automatic, easily determinable, open and above-board method of evaluating franchises. As will be recognized, the proposed method gives a different value to the franchises of different companies, but is equally fair to all because based on their tangible value: it will also be seen that the value of the franchise of a given company may vary from year to year, depending upon the value of their property. Both of these variables are essential in a franchise valuation.

Example illustrating "fair return" for New York corporation.

Life of franchise	20 years	Perpetual
Cash investment or replacement value	$300,000	$600,000
Capitalization of franchise at 33%	100,000	200,000
Total capitalization	$400,000	$800,000
All operating expenses, 40%-50% gross	36,000	96,000
Maintenance and repairs, 7% on 66% investment	14,000	28,000
Depreciation fund, 5% on 66% investment	10,000	20,000
Amortization on franchise value, 5%	5,000	......
Interest on total capitalization, 6%	24,000	48,000
Gross income	$89,000	$192,000

In making up the annual operating and fixed charges of a corporation, it is proposed that the state commission should consider the value of the franchise, as determined above, allowing the legal rate thereon and also a further amount for depreciation or amortization, depending upon the life of the franchise. This latter figure, in the case of a perpetual franchise, would be nothing; but in the case of a short-time franchise would be a very appreciable amount, which of course must be paid by the public. The economy of a perpetual franchise, which the companies desire, will be appreciated, and there is no great objection to it, provided its owner is properly restricted so as to safeguard the public interest. To illustrate the foregoing, let us consider a concrete example of a New York corporation which has been granted a liberal franchise for a period of twenty years, and has invested $300,000 in order to establish a going business, compared with a similar corporation having a perpetual franchise and an investment of $600,000 For more fully illustrating conditions as found, we will assume that the general operating expenses, in the first case are 40 per cent. of the gross income, and in the second case, 50 per cent. due to differences in apparatus installed and efficiency of management. Repairs and maintenance will be taken at 7 per cent. and depreciation at 5 per cent.

If the gross income exceeded the above figures, the price of the corporation's product should be reduced proportionately to a prearranged increase in dividends, in accordance with the London scale or a modification thereof. If the gross income were less than the above, it would be proper to increase the price of the commodity, as was authorized, for example, by the Wisconsin Public Utilities Commission in the case of the LaCrosse Gas and Electric Company.

It will be noticed from the above example, that in a different state with a different legal rate the returns allowed on the investment, and consequently the gross income allowed, would be different. This is as it should be, because the rate of return varies in different parts of the country, as is recognized by the various legal rates in the different states.

The plan suggested for regulating corporations does not place all the corporations on exactly the same basis at the start, as indicated by the example given, due to difference in efficiency of apparatus or management; but these differences are probably not greater than those which arise by reason of location, business opportunity, or public sentiment, and will doubtless about offset one another independently of the fact that the effect of the London scale properly applied has a tendency to bring all companies to the same earning basis.

If some definite plan for determining "fair return" in connection with franchise valuation, could be agreed upon and urged by any considerable proportion of disinterested people conversant with the facts, or even the corporations themselves, would not the commissions and the courts be inclined to accept and adopt such precedent thus established? The result would be a definite knowledge of what returns from public utility corporation investments could be counted upon, and what valuations would be accorded their tangible and intangible property, ignorance of which facts is the principal reason for the present unsettling of their business, undervaluating of their securities, and to some extent the discrediting of the work of the engineer.

DISCUSSION ON "THE RATIO OF HEATING SURFACE TO GRATE SURFACE AS A FACTOR IN POWER PLANT DESIGN", AT NEW YORK, DECEMBER 13, 1907.

(Subject to final revision for the Transactions.)

Chas. E. Lucke: Comparing the two curves of Fig. 4 it would appear that for an equivalent evaporation of 9.25 lb. of water per pound of coal, the ratio of boiler horse powers with double and single stokers is as 1100 is to 638, or about 1.72; with 9.5 equivalent evaporation, the ratio is as 1046 is to 609, or about 1.72; with an equivalent evaporation of 9.75 the ratio is as 996 is to 582, or about 1.71. It thus appears that when operating this boiler at capacities 1.71 times as great with double stoker as for single, the equivalent evaporation, and, therefore, the boiler efficiency, is in nowise altered. At the same time referring to the curve for single-stoker operation there is reported for 512 h.p. an evaporation of 10.50 lb., which fell to 9 lb. on an increase of boiler horse-power to 670. In this case, therefore, an increase of boiler horse-power from 510 to 670, a ratio of capacities of 1.31, the efficiency or equivalent evaporation decreased in the ratio of 10.5 to 9; or the efficiency for the higher capacity is to the efficiency for the lower capacity as 9 is to 10.5, or, approximately, 0.86. An increase of boiler capacity in a given boiler is to be obtained by burning more coal primarily. From the preceding it would appear that burning more coal under this boiler with a single stoker gave a continuous drop in efficiency; also from the other curve an increase in the burning of coal on two stokers gave a decrease in efficiency continuously, but strangely enough, a very material increase in the coal burned per hour operating double versus single, sufficiently great to increase capacity to 1.7 its original value, gave no decrease in boiler efficiency. Why is it that with a single stoker an increase of capacity from 1 to 1.3 lowers the efficiency from 1 to 0.8, while increase of capacity from single to double stokers from 1 to 1.7 does not decrease the efficiency at all.

With increase of coal burned under the single stoker, the curve falls continuously and then breaks, starting again at a high point at the beginning of the double-stoker line, along which it again falls. It would seem as if these two curves should join and be continuous, and the fact that they do not, warrants an investigation into the causes. All of the general discussions of boiler efficiency seem to concentrate the conditions for efficiency, and with some degree of reason, on two prime variables; one entering into the structure, the other the operation. The first is the ratio of heating surface to grate surface, and the other is the rate of combustion per square foot of grate surface. With a view to determining how far the ratio of heat surface of itself, independent of other things, might effect boiler efficiency, one of the students at Columbia examined some 300 boiler tests that seemed most authentic and plotted, as in Fig. 1, boiler efficiency against the ratio of heating surface to grate surface, From these data, it appears that the boiler efficiency lies between 45.4% and 84%, while the ratio of heating surface to grate surface lies between 14 and 89. The disposition of the points is such as to prevent any conclusion in the form of curves or law of relation, as they do not group themselves in any definite way, but are deposited over what has often been called "a shot-gun diagram", and not a very good one at that. It would thus appear that the ratio of heating surface to grate surface cannot of itself fix boiler efficiency, however much it may seem to be rationally related to it.

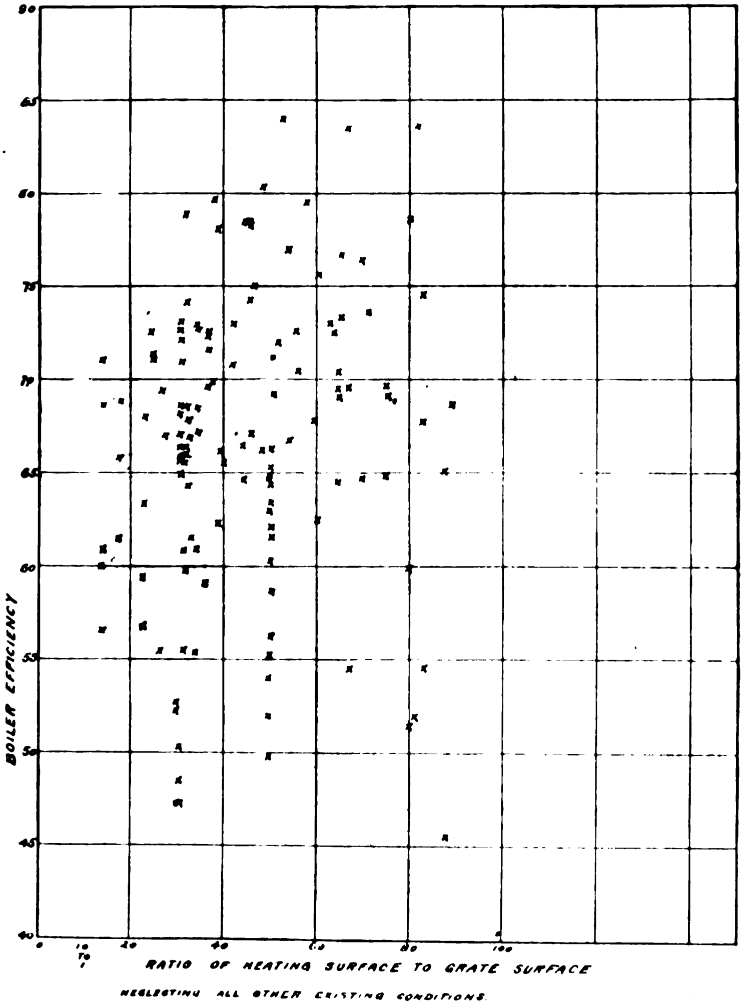

FIG. 1.

The phenomena taking place in a boiler are really quite simple. Any question of boiler efficiency resolves itself into an examination of these phenomena in an attempt to trace the losses. Neglecting all insignificant losses and assuming all coal to be burned, a boiler has an efficiency of less than 100%, because some of the heat liberated in the fire escapes; first, by radiation in an amount depending chiefly on the mean temperatures of the setting and boiler room; secondly, in the flue gases in an amount depending on their excess of temperature over the atmosphere, their weight and specific heat. To all intents and purposes the mean temperature of the boiler setting of these tests, single and double, may be taken as the same, as may the specific heat of the gases, so that any changes in boiler efficiency that occurred must be charged, assuming all the coal to have been burned, which is reasonable, to a change in the product of excess flue temperature over atmosphere and the weight of gases discharged per pound of coal.

With a given rate of heat liberation in the furnace, it is absolutely certain that the temperature of the gases passing through the boiler will continuously fall as they travel toward the flue. Thus, there might be plotted a falling curve of temperature with the path of these gases through the boiler. A very material increase in rate of heat liberation without change in the weight of air per pound of coal would have the effect of displacing this falling curve completely toward the flue end, or in other words, of raising the temperature at every point in the path and likewise raising the temperature at the flue, so that flue temperature would continuously rise with an increase in rate of combustion, perhaps slowly at first, and faster with the higher rate; boiler efficiency will thus continuously fall with increase in rate of heat liberation or weight of coal burned per hour without any increase of excess air, by reason of this rise in the flue temperature. Admission of more excess air with the higher rates might keep the temperature from rising, but still involve decrease of efficiency. An increased rate of heat liberation or pounds of coal per hour burned may be accomplished by an increase of the draft to raise the rate of combustion per square foot of grate per hour or by increase of surface without increase, perhaps with decrease, of draft. If by reason of a certain stoker construction or by reason of the manipulation of any given stoker, the air supply increases faster than the coal burned per hour, so will also the excess air and the weight of total gases per pound of coal. There is thus a possibility that with increase in rate of combustion per square foot of grate surface there may be also an increase in weight of gases per pound of coal by an increase of excess air, which would tend to decrease the boiler efficiency.

An examination of the results of this test does not indicate from the curve for either the single or the double stoker which factor was more potent in decreasing boiler efficiency with increase of coal burned per hour—the flue-gas temperature or the excess weight of gases, but comparing the double-stoker curve with the single and finding thereby that the same boiler efficiency corresponds to the same rate of combustion per square foot of grate, it would seem that the excess-air factor was more potent than the flue-gas temperature factor. It is inconceivable to me that increasing the coal burned per hour from 2370 for the single stoker to 4100 for the double stoker, or

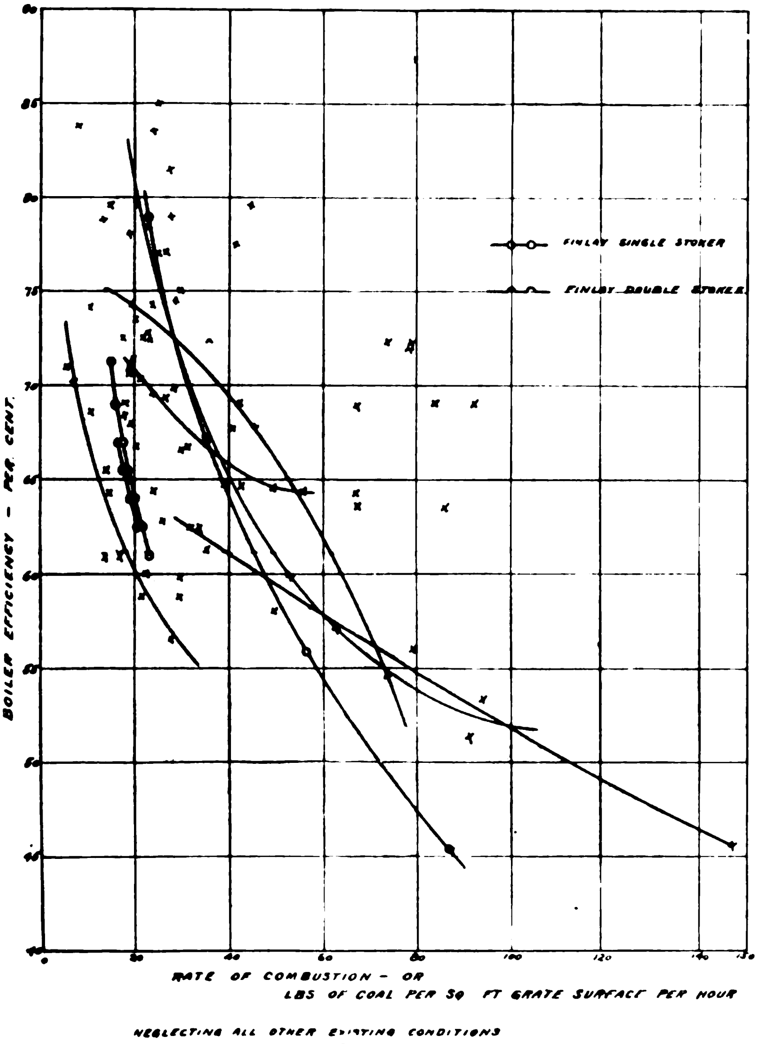

Fig. 2.

1.74 times as much, which corresponds to 9.25 evaporation for both cases, there should have been no change in the boiler efficiency if the weight of gas per pound of coal was the same in both cases, especially as with the higher rate the time of contact between gas and boiler tubes is very much less than for the lower rate. The flue temperature for the double-stoker operation must have been higher for the same excess air, and the fact that the efficiency was not any lower seems to indicate that the excess air was less in proportion or that in single-stoker operation, very much more excess air was used than for double-stoker operation. While I believe that two boiler efficiency curves should not be compared except on equal terms, which in this case would be on a basis of equal flue-gas composition, still such a course might be justified if, under the conditions of usual operation, the furnace were such that it could not be operated with the same excess air under different ratings, which would be a most severe criticism of the furnace and not of the boiler. If this is the true explanation, the paper would become a discussion of furnace operation as a function of draft and rate of combustion. The true explanation must depend on the presentation of data on flue-gas composition and flue temperatures.

If on analysis of the efficiency results it should appear that they are due to a comparison of two boiler tests on unequal terms of flue-gas composition, and that for equal flue-gas composition the efficiencies for double-stoker operation are lower than for single at equal capacities, then the conclusions on cost economy might be reversed. For example, if higher flue temperatures result from high capacity of operation, then more economizer surface must be used to attain equivalent plant efficiencies, and discussions of plant cost economies must resolve into a comparison of the commercial value of heating surface in the form of boiler with that of heating surface in the form of economizer.

W. F. Wells: The ratio of heating surface to grate surface, although a question of primary importance, is to my mind a matter of secondary consideration. In order to design the most suitable boiler plant for a power house that can be constructed at a minimum cost per kilowatt installed, consideration should first be given to the evaporation possible per square foot of heating surface consistent with commercial economy; and this in turn depends upon the maximum practical rate of combustion of the various fuels available in the local market, their relative costs per ton, cost of handling, and thermal values.

Mr. Finlay's statement that "a considerable increase in boiler capacity can, without great sacrifices in economy, be obtained by proportional increase in grate area" is applicable to most power plants, because until very recently, power house engineers have endeavored to obtain the greatest economies possible from boilers by proportionally increasing the heating surface, so that the average boiler of to-day will give but little more than rating when fired with the so-called " steam coals ". In other words, most boilers, as installed on land, are rated on a basis of 10 sq. ft. heating surface per horse-power and will evaporate but 3.5 pounds of water per square ft. of heating surface, whereas, in marine practice double this amount, or 7 lb. of water, can generally be evaporated per square foot of heating surface; and with closed stoke-hold and forced draft, three times boiler rating, or 10.5 lb. of water, can be evaporated per square foot of heating surface and even greater is sometimes possible.

The following table shows that under the single stoker boiler, referred to in the paper, having a *ratio of* 1 : 56, it is necessary to burn about 20 lb. of coal per square foot of grate, in order to evaporate 3.5 lb. of water per square foot of heating surface, and that by burning 25 lb. of coal, which is about the maximum that can be burned commercially on a mechanical stoker, the boiler will develop only about 20 per cent. above rating. With two stokers under the boiler, making a ratio of 1 : 31, 7 lb. of water can be evaporated per square foot of heating surface, or double boiler rating.

The flat grates originally installed in 1901 under the boilers at the Waterside Station of the New York Edison Company had a ratio of 1 : 74, and in order to obtain boiler rating, it was necessary to burn 35 lb. of No. 3 buckwheat coal per square foot of grate, which necessitated hard firing and great care. The same output could be obtained by firing 28 lb. of No. 1 buckwheat, or 31 lb. of a mixture, consisting of 20 per cent. soft coal and 80 per cent. No. 3 buckwheat. This, however, meant a loss in commercial economy on account of the higher cost per ton of fuel. By extending the fronts of the furnaces under these boilers, and enlarging the grates, thereby reducing the ratio to 1 : 59, it was possible to obtain boiler rating with 25 lb. of No. 3 buckwheat, 22 lb. of No. 1, or 24 lb. of the mixture. With those extended grates, 50 per cent. above rating could be obtained by burning 40 lb. of No. 1 buckwheat per square foot of grate per hour. This firing is possible with forced draft, but great care must be used in order to maintain economy.

In the Sixty-sixth street station of the Brooklyn Edison Company the grates were originally installed with a ratio of 1 : 68, but last summer the fronts on these furnaces were extended and grates enlarged, giving a ratio of 1 : 53. This increase in grate area was utilized not so much for increased capacity as to give increased economy by burning a cheaper fuel. The economy actually effected by this increased in grate area amounted to 14 per cent. in cost of evaporating 1000 lb. of water.

At our Gold street station, the grates as originally contracted for three years ago were at a ratio of 1 : 76, but before installing the furnace, fronts were extended, thereby reducing the ratio to 1 : 59, and under the boilers installed in 1907 by moving back the bridge-wall, this ratio was still further decreased to 1 : 52. Under boilers proposed for 1908, this ratio has been reduced to 43.

With this ratio of 1 : 43, almost double boiler rating can be obtained, or 7 lb. of water per square foot of heating surface, can be evaporated by burning No. 3 buckwheat, and double rating probably exceeded by burning No. 1 buckwheat or a mixture. This ratio would have been made less but for the physical impossibility of handling a deeper fire box.

It must not be assumed that the least ratio practicable is the best, as there is a possibility of making the grate too large for the heating surface. In addition to the disadvantage of the loss of economy, due to excessive flue temperatures already mentioned, there is the necessity of banking boilers at times of light load, and the loss of time and labor necessary again to bring the fires into condition for steaming.

Walter T. Ray and Henry Kreisinger (by letter):* Perhaps the first inkling that something was wrong came when a number of operating engineers in various places began to explore the interior gas passages of water-tube boilers with thermocouples, and found large dead corners. We have carefully explored many boilers and have never failed to find room for improvement, provided only that it is mechanically feasible to insert gas baffles so as to cause the gases to reach a greater portion of the heating surface, at the same time permitting the gases to travel over the whole surface with at least as high an average velocity as before.

This latter point is important, for practically no benefit would come from inserting baffles such as would cause the gases to flow into dead corners, if at the same time the gas velocity over the old portion of the heating surface were proportionately reduced. The velocity of the gases over, (or past, or along), the heating surface is the active feature which determines how much heat will be imparted to the surface, other things being equal. If the velocity of gas be doubled, the amount of steam produced per second will be nearly doubled. For a fuller discussion of this matter we refer to the Geological Survey's bulletin entitled " A Study of Four Hundred Boiler Tests ".†

The possibility of greatly increasing the rate of heat transmission into boilers will be apparent when it is considered that the amount of heat which can be passed through a thin metal plate is enormous. The heat-resistance of the metal in the case of boilers is insignificant, perhaps ordinarily much less than, $\frac{1}{100}$ of the whole; the seat of resistance is in the layers of scale and soot, and, most of all, probably, in the films of gas adhering to the soot and of steam and water adhering to the scale. If these are reduced in thickness by increasing the velocities of the streams of gas and water rubbing against them, the rate of heat transmission will be greatly increased. This is not mere theory, but has been experimentally demonstrated on laboratory models and on large boilers.*

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* We wish it distinctly understood that the United States Geological Survey is in no way officially committed to any of the opinions advanced hereafter. Presented with the permission of the Director of the United States Geological Survey.

† Bulletin No. 325, United States Geological Survey, Washington, D.C.

The great increase in capacity in the case cited by Mr. Finlay was undoubtedly due to the increased velocity of the hot gases over the heating surface of the boiler. By burning 80% more coal, the weight of hot gases generated per second was increased by the same amount. In passing this increased weight of gases through the same boiler the velocity was increased by the same percentage, resulting in an increase of 80 per cent, in capacity.

Mr. Finlay has made only a beginning in working his boilers harder. The Interborough Rapid Transit Company has verified the conclusions experimentally reached mathematically by Professors Reynolds Perry of England. It is our personal opinion that the boilers under consideration could probably stand five passes instead of three, and that perhaps some other minor changes would be beneficial.

Mr. Finlay's device of putting two stokers under one boiler accomplished the burning of more coal without working the combustion chamber any harder; that is, without increasing the velocity of gases from grate to tubes. Such an increase would have resulted in lessening the time available for the combustion of certain gases. It will be noticed that the distance from the old grate to the entrance into the tubes is only about one third the distance from the new grate to the same entrance; it is therefore likely that the gases from the new stoker are more completely burned, and so it is not surprising that on heavy loads the evaporation per pound of coal was as high as at lower loads on the old stoker alone. The point we wish to emphasize is, that the efficiency of the boiler as a heat absorber is practically constant and independent of the rate of working. The boiler will do its part in meeting increased demands for steam.

In the Jamestown-Exposition Plant of the Geological Survey is a 210 h.p. boiler which has been so re-baffled as to cause the gases to pass through the tubes twice instead of once. They pass through a smaller cross-section, nearly twice as far, at a higher average velocity, with the result that about ten per cent. more heat is absorbed, accompanied by no reduction in capacity when using the same draft. When the draft is raised and the boiler made to produce about twice its rated amount of steam, it still retains nearly all of its increased efficiency. Here is a case of greatly increasing the output at a slight cost and at the same time increasing the economical evaporation per pound of coal.

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* See "The Nature of True Boiler Efficiency," by Walter T. Ray and Henry Kreisinger, September 18, 1907, Western Society of Engineers, Chicago

We see no reason why boilers can not be so designed as to yield several times as much steam per square foot of heating surface as they now do, and with a considerable increase in economical evaporation. One thing seems inevitable—complete resort to forced or induced draft, or, better still, to both.

W. L. Abbott (by letter): Mr. Finlay assumes the cost of a plant to be $125.00 per kilowatt and of this the cost of the building is 35 per cent, or, $43.75, and also that the size of the building is determined by the number of square feet of heating surface in the boilers. He therefore proposes to re-design the plant, using only half as much boiler heating surface, but worked to double the former capacity, thereby effecting a saving of $23.58 per kilowatt in the cost of the plant of which amount $17.50 is due to a reduction of 40 per cent. in the size of the building.

While the foregoing assumptions may have been correct a few years ago, they certainly do not apply to more recent designs for turbine plants using large generating units. In these designs the size of the building is not determined by the number of boilers any more than it is determined by the number of turbines, and the cost of the building, which is about $15.00 per kilowatt, is divided about equally between the boiler room and the rest of the plant. The reduction of 40 per cent, in the cost of the building incident to a reduction by one-half of the boiler heating surface will therefore be applied only to a $7.50 boiler room and not to a $43.75 power house building.

Again, Mr. Finlay allows an additional loss of only 3 per cent. of the fuel when he doubles the rating of a given boiler. This assumption is probably correct for a boiler having an ample economizer, but in the case of a boiler not so supplemented, the additional fuel loss would undoubtedly be as much as 10%, and it should be stated here that the figures given above for cost of boiler room do not allow space for an economizer.

We now have the following approximate figures for power house costs:

With boilers of standard rating	$96.00
" " double " "	$93.00

Both of these prices are without economizers.

Taking these new figures and calculating the data for curves similar to those given on page, 1695, it appears that the total cost of current output will be practically the same in both cases, regardless of the rating at which the boilers are worked.

A. Bement (by letter): It is rather remarkable in the tests described by the author, how nearly constant final efficiency is in steam generation with one and two stokers, and this may be partially explained by the fact that the proportion of the usual type of water tube boiler is such that only a part of the tube surface is acted upon by hot gases, and if a larger volume is forced over the boiler, as would occur with two stokers, their relatively greater body, demanding more space, will extend to portions of the boiler which were practically unused with a single stoker. This has been illustrated elsewhere.*

Referring to Fig. 7, which shows an elevation of boilers and stokers in the Subway power plant, it would appear that a furnace roof has been improvised by the insertion of a baffle between the tubes of the two lower rows of the boiler in the rear. If this be true, it leaves the lower row of tubes exposed to the heat from both stokers for about five-sixths of their length. I would inquire if it has been possible to operate these boilers to to any considerable extent without destroying the tubes of this bottom row by overheating. Even if they have been able to stand such an amount of work, this design of furnace could be very much improved by the use of an encircling tile which are usually made in lengths of 12 in. as have been elsewhere described.† This would not only reduce the amount of work required of the bottom tubes, but would furnish a more satisfactory roof than an inserted baffle does.

W. S. Finlay (by letter): It is evident that the discussion has been productive of possibly more valuable experimental results than are contained in the paper itself, and to attempt to reply to each and every feature of the very long and elaborate criticisms, would be absolutely out of the question. What may be said in reference to these discussions, is said with due respect and recognition of the greater knowledge and experience possessed by the gentlemen whose work determines the value of the subject in hand.

Possibly it was unfortunate that more emphasis was not given to the fact that the specific solution of the problem of increased efficient combustion; namely, the double stoker, was not proffered as a general or sole solution, but was quoted as merely one form, convenient and satisfactory in the case to which it was applied. Neither did the writer desire to give any specific value to the ratio, simply wishing to emphasize the importance of its careful consideration under attendant conditions.

With reference to Dr. Lucke's criticisms, which are chiefly from a theoretical standpoint, a reply should be given from a similar basis. A careful study of the discussion shows that there has been practically but one point brought up, this point being repeated in a number of different ways. In form, the discussion is interrogative, tending to throw a doubtful light upon the experimental data referred to in the paper. A declarative form might be stated as follows:

1. Operation under double-stoker conditions should theoretically conform to operation under single-stoker conditions. With increased total combustion, and increased capacity, economy should decrease regularly, if expressed graphically, in a single continuous curve, whether such increase in capacity be accom-

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*Transactions American Society of Mechanical Engineers, Vol. XXVI, p. 626.

† Journal Western Society of Engineers, Vol. XI, p. 752.

plished by increased combustion upon a single stoker, or upon a double stoker.

2. Boiler efficiency is conditioned upon two variables:

a. Ratio of heating surface to grate surface.

b. Rate of combustion per square foot of grate surface.

The question has thus been reduced to a study of: first, that which actually determines boiler efficiency; secondly, the form in which this efficiency varies.

It is a self-evident fact that a diagram, such as the " shot-gun " diagram, based upon results of three hundred tests under all sorts of conditions—boilers, combustion chambers, etc.—is of little or no value, and useless so far as it bears upon theoretical investigation.

The rate of combustion must be recognized as a factor in the " unit " efficiency under practical conditions, but as to its effective value so far as the boiler proper is concerned, it would, in the light of recent investigation, seem highly probable that boiler efficiency decreases but little under conditions of increased rating.

Merely to consider two factors determining boiler efficiency, namely: 1. The ratio of heating to grate surface—primarily a specific feature, which can not be generalized—and, 2. The rate of combustion, would be obviously to neglect certain most elementary and fundamental features in design.

It is inadvisable to attempt completely to discuss all factors entering into boiler and grate efficiency, particularly as certain new features in theory and experiment indicate that knowledge of the subject is not at all complete. However, a summary of recognized factors from both theoretical and practical points of view will serve to indicate the relative effective value of each upon the efficiency of the boiler when considered as a unit consisting of boiler proper, furnace, and grate. Thus, for any given set of conditions, unit efficiency will depend upon the following factors:

1. Grate design, a factor involving in practice relative values, of air-space, adaptability to grade of fuel, ease of handling in process of cleaning, with attendant effect due to admission of excess air, etc.

2. Furnace design, which involves complete combustion of gases, and transmission of the same to the heating surface when at their maximum temperature.

3. Method of air supply, which must naturally be considered together with the preceding factors.

4. Boiler design, which may be sub-divided as follows:

a. Relative exposure of heating surface to heat radiation from fire and furnace walls.

b. Design of heating surfaces in relation to direction of quantitative flow of gases.

c. Design of baffling as effective upon flow of gases, with due regard to the effect of such baffling upon soot accumulation, and " dead " space; also to direction of circulation in boiler.

d. Boiler design in respect to rapidity of circulation of water.

5. Boiler proper, maintenance and operation. This factor includes cleanliness in inner and outer surfaces of tubes and drums, together with the condition of all parts of the unit. Operation includes care and handling of fire, together with manipulation to obtain best combustion and lowest practicable flue-gas temperatures.

A number of other governing factors might be quoted, but for purposes of comparison the above will suffice.

A comparison of conditions existing in the single- and double-stoker boilers as influenced by changes in certain of these factors, will serve to explain the apparent discrepancies which Professor Lucke calls attention to. In the change from single to double stokers, the only factors vitally affected, are:

1. Furnace design, in which case the new design undoubtedly favors a more complete combustion of gases, a point in favor of increased efficiency.

2. Grate design, the possibility of increasing combustion per square foot of heating surface without a tendency to force excess air through the fire.

3. Increased exposure of heating surface to radiation from the fire-bed.

4. Greatly increased volume of flow of hot gases; larger portion of the heating surface becoming active, and dead spaces and eddy currents of gases decreasing in number and effect. Heat convection to heating surface is increased by reason of greater speed of gas circulation.

5. Boiler operation is improved by reason of the fact that increased water circulation tends to lessen the formation of scale, as well as improved heat convection inside of tubes.

The above summation of changes in conditions, with their effect upon the unit efficiency, tend to show that curves plotted upon bases of efficiency and rating for the single-stoker boiler and the double-stoker boiler need not be identical, the one a continuation of the other. These curves would necessarily be distinct and individual for each set of conditions.

It is to be noted, in the particular case of the efficiency curves given, that the decrease in efficiency for increase in rating seems to be rather rapid. To lessen the slope of these curves, the self-evident solution is to provide such draught or air-supply conditions that forcing of fires would not be accompanied by excess air supply or undue disturbance of fires.

A move in this direction, with apparently successful results, has already been taken; but the fact remains that the double stoker must retain the all-round higher grate efficiencies accompanying combustion at a lower rate per square foot of grate surface, together with improved furnace conditions. The feasibility of obtaining efficiently high boiler output, with due consideration of total plant charges and costs, makes the double-stoker simply one device to obtain certain results, its choice to be based upon ruling conditions.

Mr. Wells bases his entire discussion upon a premise whose value is exactly the point which originated the question brought up by the writer. He makes the statement:

> Consideration should first be given to the evaporation possible per square foot of heating surface consistent with commercial economy; and this in turn depends upon the maximun practical rate of combustion, etc.

This is just a re-statement of heating surface and furnace relation. However, having made this statement as the fundamental, his development of the subject has unfortunately been merely under lines of hitherto accepted methods of increasing boiler capacity without any consideration of the latest phases of development giving consideration to the possibilities latent in heating surface efficiency.

The discussion by W. T. Ray and H. Kreisinger is peculiarly valuable in view of the fact that it incorporates results of most recent investigation. The writer considers it a most practical verification of what has been said in reply to Dr. Lucke's discussion as well as of the original paper.

It is evidently a misinterpretation of the writer's thought that Messrs. Ray and Kreisinger have emphasized the point of fixed valuations to the ratio of heating to grate surface. The writer fully realizes that such a fixed valuation could not be generally applied, the purpose in view being more particularly a careful consideration of furnace and heating surface relation, as applied to each specific case in the light of results such as have been realized by the very investigations of the United States Geological Survey.

Mr. Abbott objects to considering the size of the boiler plant as practically the determining factor in the size of a plant building. Conservative design, as exemplified in nearly every recent plant of importance, has been on the parallel plan, it being almost uniformly an accepted rule that consideration must be given to plant growth and extension, in addition to uniformity, as necessary to simple operation. The turbo-generator in point of permitting extreme flexibility in adapting turbine room size to boiler room size has been an additional incentive to the development of this system.

Replying to Mr. Bement's first question in reference to the life of the bottom row of tubes, the writer would say that operating results for a period of about three months show most satisfactory results in this regard. Improved circulation and evenness of heating of these tubes results in improved cleanliness and little wear. Mr. Bement's statement in reference to increased utilization of heating surface in the case of the double stoker seems to corroborate the reply to Dr. Lucke's discussion.

DISCUSSION ON "AN EXHAUST STEAM TURBINE PLANT", AT NEW YORK, DECEMBER 13, 1907.

(Subject to final revision for the Transactions.)

Francis Hodgkinson: The combination of a turbine utilizing steam at atmospheric pressure in conjunction with a reciprocating engine is by no means new, although the one described is probably the first installation in this country of such apparatus in conjunction with a Rateau heat accumulator. However, leaving out any value there may be in the heat accumulator, there is no doubt that power plants now operating non-condensing and requiring increased capacity would do well to obtain it by low-pressure turbines so long as means of condensing the exhaust steam are available within reasonable expense. There are many power plants employing high-grade compound reciprocating condensing engines where the total expansion is such that the engines have a higher efficiency ratio when operating non-condensing (efficiency ratio, not steam economy), than when operating condensing. In making this statement I have more in mind high-grade engines for modern power plants, than such prime movers as blooming-mill engines where the expansion when exhausting even to atmosphere is somewhat incomplete. The power-plant engineer, therefore, should not expect to make the large percentages of increase in economy that the author cites in the case of the Wisconsin Steel Company, and the Poensgen steel works, at Dusseldorff.

In the case of the Dusseldorff installation, presumably most of the engines were simple engines; if compounded at all, it was probably with low cylinder ratios. Hence, merely turning the exhaust from these into a condenser would not make material difference in the steam consumption; but exhausting them instead through a low-pressure turbine, and thence into the condenser would, if the power from the turbine be made use of, cut the steam consumption per unit of power to about one-half what it was before.

Low-pressure turbines are not only applicable for working in conjunction with non-condensing reciprocating engines in which the steam expansion is incomplete, but just as much in conjunction with engines designed for operating condensing. A low-pressure turbine can, furthermore, just as well be designed to operate at less than atmospheric initial pressure, should the performance of any given high expansion ratio reciprocating engine show a higher efficiency ratio when exhausting at some pressure less than atmosphere.

One obvious reason for the beneficial results of low-pressure turbines is due to the large temperature drops as low steam pressures are reached, which in the low-pressure cylinder of the reciprocating engine are harmful because of condensation and re-evaporation as the cycles are reversed. This objectionable condition does not exist in the low-pressure turbine.

As an instance of the advantage of low pressure turbines, assume a compound reciprocating engine of cylinder ratios of 3.5 : 1, say of diameters 28 in. and 52 in.; this with 150 lb. initial pressure may be assumed of 1000 k.w. economical capacity when running condensing and having a steam consumption of about 22 lb. per kilowatt-hour. This engine, if operated non-condensing, could have valve gears adjusted to develop 1,700 i.h.p. when it would consume about 20 lb. of steam per i.h.p. per hour. This gives 30,600 lb. steam available for the turbine, allowing 10 per cent. of moisture in the exhaust of the reciprocating engine. The total amount of steam passing the reciprocating engine, however, being 34,000 lb. 30,600 lb. would develop not less than 1,073 brake horse power in the turbine. Allowing 94 per cent. for the mechanical efficiency of the reciprocating engine, the combined horse power developed would be 2,673 brake horse power and the steam consumption of the two units 12.7 lb. per brake horse power-hour, or 18 lb. per kilowatt-hour, which is a remarkable performance for engines of such capacities operating without superheat. Compared with the performance of the reciprocating engine running condensing, this gives 75 per cent. increase of power and 18 per cent. saving of steam.

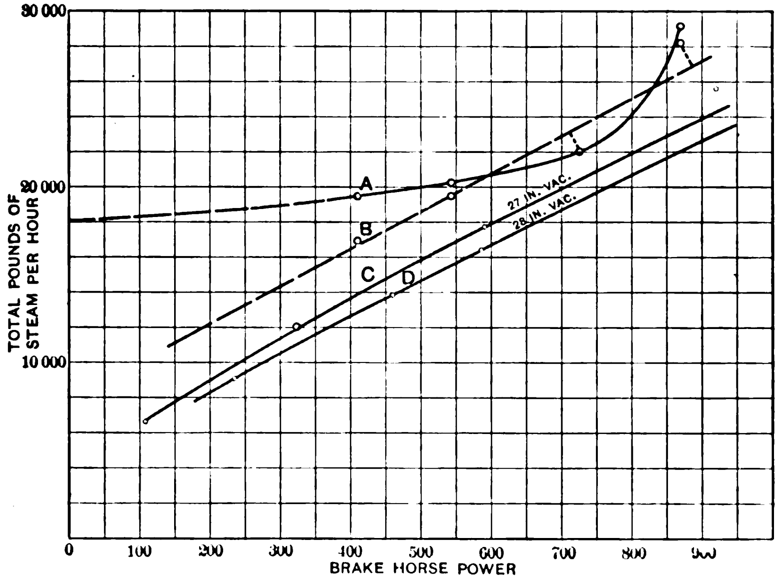

Fig. 1

One very nice feature of low pressure turbines when used in conjunction with reciprocating units where the electric energy from each may be connected to the same bus-bars, is that the turbine need have no governor other than a safety stop. In the case of alternating current generators, they are locked together, electrically, the steam turbine doing all the work that it can within its pressure limits and in the event of the load becoming light, the available steam will be proportionately reduced by the governors on the reciprocating engines. In the case of direct current units the generators may be shunt wound, which makes them self-regulating in a precisely similar manner, inasmuch as the voltage varies nearly directly as the speed, and the load will divide itself properly between the reciprocating unit and the turbine.

A low pressure turbine built for such purposes naturally contains very few rows of blades as compared with ordinary turbines, the volume of steam being large permitting generous blade proportions and having neither regulating valve nor governor mechanism, must commend itself as the simplest kind of apparatus imaginable.

Examining the tests which Mr. Wait quotes in detail, we find that the curves show the steam consumption per brake horse power per hour. The general characteristics of a turbine are, however, much better exhibited by a curve of total steam consumption; to show it in this case, I submit Fig. 1 where the total steam consumption per hour is shown by curve *A*. It is unfortunate in the tests quoted by the author, that the vacuum was not maintained constant at the various loads, for the line of total steam consumption is very much curved. It is the writer's experience that the line of total steam consumption for low pressure turbines is a straight line, just the same as it is in the case of standard condensing turbines. Of course had the vacuum been kept constant the curve would have been more nearly a straight line. Correcting this curve to constant 27 in. vacuum in accordance with the writer's experience with varying vacuum, indicates the performance of the low pressure turbine to be about as curve *B*.

We note in the tests, the generators have been assumed to have constant efficiency at all loads tested.

Some tests on a low pressure turbine made recently gave the following results:

Steam pressure pounds per square inch absolute. Dry and saturated steam	Vacuum in exhaust inches mercury, referred to 30 in. barometer	Load in brake h.p.	Total steam per hour	Steam consumption brake h.p. hour
17.4	25.98	920	25670	27.9
12.4	25.99	472	17487	37.1
11.8	26.97	592	17720	29.9
7.7	27.03	321	11980	37.3
5.2	26.98	102	6570	64.4
11.6	27.8	586	16400	28.00
8.7	28.00	458	13920	30.4
6.1	27.90	234	9036	38.6
4.5	27.99	114	6248	54.8

It will be observed from the above table that various loads were carried at constant vacuum, and sets of tests were also made with different vacuum. In these particular tests high-pressure steam was used, but care was taken to inject enough water to reduce the superheat at the inlet pressure to zero The results of two of these sets of tests: namely, at 27 in. and 28 in. vacua, are shown in Fig. 1 and from these were deduced the corrections to constant vacuum which I have applied to the authors test.

Another turbine built to operate in connection with high-pressure reciprocating engines gave the following result in shop test:

Initial steam pressure, 15 lb. absolute.
Superheat 40° fahr.
Vacuum referred to 30 barometer—23 in.
Load 1500 brake h.p.
Pounds steam per brake h.p.-hour 35.5.

In all these tests the exhaust was condensed in a surface condenser, which assures accuracy in measuring the steam consumption.

The author makes some remarks on the subject of condensers as applied to low-pressure turbines and endeavors to show what vacuum it is most expedient to carry with different conditions of temperature, etc. He draws his conclusions largely from the power required to operate the condenser, which he assumes to be motor-driven. Except when motor-driven, the power required to operate the condenser does not necessarily have much bearing on the case. There are many reasons why it is preferable, as is customary in this country, to operate condensers by means of non-condensing steam engines, the exhaust of which is condensed in feed-heaters. So long as this steam is utilized, the thermal efficiency of the engines will be something like 87 per cent., as has already been pointed out by Mr. H. G. Stott, in his paper on " Power Plant Economics ", so that where the exhaust steam is thus profitably used the amount of power required to operate the condenser is almost immaterial.

It is unfortunate we are not given more information regarding the performance of the heat accumulator, especially as to how much energy it is capable of storing up and giving out. We calculate from the published description that the regenerator has normally 100,000 lb. of water in it. Mr. Wait says it blows to atmosphere at three pounds' gauge pressure, 222° fahr. The reducing valve admits live steam at atmospheric pressure 212° fahr. and that the regenerator normally works between these limits. This gives a temperature range of 10° and Mr. Wait says the turbine will carry load for 7 min. without exhaust steam from the reciprocating engine or the admission of live steam. With this range of temperature, the regenerator will take up and give out 1,000,000 B.t.u. the equivalent of

$$\frac{1{,}000{,}000}{961.8^*} = 1040 \text{ lb. of steam.}$$

which will run the engine $\frac{1040 \times 60}{27{,}000} = 2.31$ min.

27,000 being the assumed steam consumption of the turbine. The other 4.69 min. to make up the 7 min. quoted by Mr. Wait, requiring 2110 lb. of steam would be accounted for if there were 280,000 cu. ft. contents in the receiver, steam space of regenerator, piping, etc.

I should think that better results would be obtained from the regenerator by having the turbine large enough to carry its load without the reducing valve having to admit live steam until the temperature has fallen to, say 180°, when something like three times the heat will be absorbed and given out by the regenerator.

J. R. Bibbins: It is interesting to note that the steam velocities are reduced to so a low point by subdivision of the expansion into a large number of stages, that no appreciable erosion has resulted from moisture in the steam. This, of course, is an extremely desirable feature, particularly for a low-pressure turbine in which the maximum amount of suspended moisture is found, as compared with the high-pressure element of a complete machine. In a standard complete expansion turbine operating on superheated steam, the so-called "dew point" where moisture begins to appear, may not occur until a considerable number of expansion stages have been transversed by the steam; so that while part of the high-pressure section of the turbine runs in superheated steam, the steam traversing the low-pressure section increases in moisture more or less approximating the adiabatic law. For instance, assuming ideal adiabatic expansion between the limits of 165 lb. absolute and 28 in. vacuum, the moisture in suspension would gradually increase to about 23 per cent. In practice, however, internal heat interchanges, considerably reducing this moisture, perhaps as much as 50 per cent. Thus, the low-pressure turbine is obliged to work with steam containing large amounts of moisture, and the necessity of low steam velocities is apparent, not only as affecting depreciation, but also efficiency.

In actual installations of low-pressure turbines, it is possible to trap out some of the suspended moisture in the engine exhaust and deliver steam approaching a dry saturated condition to the turbine. Here the average moisture encountered in the low-pressure turbine would evidently be lower than in the corresponding expansion stages of a complete expansion turbine operating on saturated steam. Or a heating chamber might be introduced between engine and turbine for the purpose of completely drying, or slightly superheating, the low-pressure steam. Owing to the low temperatures at which this could be accomplished, it is possible that some of the waste products of a factory or power station might be utilized to good advantage—hot gases from heating furnaces, possibly boiler-flue gases, in cases where underground flues were employed leading to the chimney.

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*961.8 is taken as the mean heat of evaporation between steam at 212° and 222°.

Although it is true that the impulse or velocity type of turbine may have as large peripheral clearances as desired around the bucket-wheels, it must not be inferred that correspondingly small clearances at the shaft are not necessary to prevent the leakage of steam between the various pressure stages, also that the side clearances between the buckets and nozzles must be small, while in the reaction or pressure type turbine the side or axial clearances may be made as large as desired without affecting the efficiency, owing to the fact that the entire steam space or annulus surrounding the rotor is always filled with working steam.

As low-pressure turbines are usually started under vacuum, provision must be made for flooding the water packing until the turbine picks up its speed sufficient to provide its own water-seal. This, of course, is easily accomplished from the ordinary water service pressure; otherwise, the vacuum would be seriously interfered with by the air leakage.

DISCUSSION ON "A NEW CO_2 RECORDER", AT NEW YORK, DECEMBER 13, 1907.

(Subject to final revision for the Transactions.)

A. A. Adler (by letter): The CO_2 determinations are not the only determinations to be made in the proper estimation of furnace efficiency, as a low percentage of CO_2 may be due either to too much, or too little air. When too much air is admitted through the furnace, the O determinations will show a high percentage; when too little air is admitted, the carbon burns to CO and CO_2, and no oxygen will be found in the analysis. The CO_2 recorder, therefore, only indicates that there is something wrong, and leaves it for the attendant to find the real cause.

Again their is a great difficulty in obtaining the proper sample to be analyzed, and the exact location cannot be determined at random. In the opinion of the writer, it should be taken before it enters the flue on the " boiler side " of the damper, so as to eliminate the errors due to infiltration of air, when natural or induced draft are used. Frequently the infiltrated air produces combustion in the flue, when CO is present, and the temperature of the flue gas rises at the far end of the flue. Such an occurrence shows an erroneous CO_2 determination, as that combustion does not benefit the boiler.

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DISCUSSION ON " A SINGLE-PHASE RAILWAY MOTOR ", AT NEW YORK, JANUARY 10, 1908.

(Subject to final revision for the Transactions.)

L. B. Stillwell: The announcement of a new motor is always interesting. When its novel features are such as tend to material improvement of performance or reduction of cost, it is not only interesting but important. When to improvement of performance and reduction of cost is added the consideration that the new motor is of a type upon the success of which depends largely the solution of the most weighty problems that electrical engineers are called upon to solve, the publication of the results of the inventor's work is an event in the annals of engineering.

Mr. Alexanderson and his associates are to be congratulated upon the production of a single-phase alternating-current motor possessing apparently at least one feature of marked originality and of much practical value—the elimination of the idle resistance in the armature winding is an important step. I have not been able to ascertain from the paper how much this step costs in other directions. The author states frankly that the motor is a compromise, combining, as he believes, the good features of the series compensated motor with those of the repulsion motor. Whether the compromise is an advantageous one, whether the characteristics of the new motor, under the conditions imposed in practical service, are such as render it, on the whole, superior to its competitors, is the question at issue.

The question of superiority is to be determined by comparison, not of one but of a number of factors. The strong point of the new motor appears to be its ability to commutate at high speed without sparking; at the moment of starting, however, the sparking apparently may be serious. Further light should be thrown upon this point. It would be interesting also to know what the power-factor is, both at starting and at speed.

But more important than either of these is the ratio of output to weight, since in heavy railway traffic motors must be placed within certain defined limits of space; for other things being equal, the best motor is the one that, within such limits and within reasonable limits of temperature and commutation, is able to deliver the largest sustained output.

In the paper presented at the 214th meeting of the Institute by Mr. H. S. Putnam and myself, entitled, " On the Substitution of the Electric Motor for the Steam Locomotive ", the question whether 25 cycles or a lower frequency; for example, 15 cycles, should be adopted for heavy railway work was asked, and the opinion was expressed that " a frequency of 15 cycles is preferable and should be adopted ". The oral discussion was energetic, and in the written discussion with which it was closed Mr. Putnam and I incorporated the following statement of opinion and summary of the positions taken by a number of distinguished engineers who had participated in the discussion:

> The oral discussion which followed the presentation of the paper was conclusive, beyond our expectation, as regards frequency. So far as the

general practice of engineers who may adopt the single-phase alternating current is concerned, we regard the matter as practically settled by the facts and opinions brought out by the discussion. The designing engineers of both the Westinghouse and General Electric Companies testified emphatically to the great increase in power of motors which can be realized by reducing the frequency, and while several speakers questioned the wisdom of now adopting a standard, no one came forward to argue that the higher frequency is preferable.

Mr. Lamme, to whom, more than to any other man, we owe the single-phase motor, stated that at 15 cycles the output of a given motor is from 25% to 40% greater than at 25 cycles and that his company had verified this by actual test.

Mr Storer testified that: ' You can get at least 30% greater output from motors with 15 cycles than with 25 cycles '.

Mr. Slichter, the engineer of the General Electric Company, who has immediate charge of the work of designing single-phase motors, said: ' There seems to be a unanimous opinion that the output of the motor may be increased some 30% to 35% by a decrease in frequency from 25 to 15 cycles '.

Mr. Potter, chief engineer of the Railway Department of the General Electric Company, after pointing out some of the difficulties in the way of the adoption of 15 cycles, said: ' I do not think, however, that we can look for the ultimate development of the single-phase motor of 25 cycles '.

* * * *

The paper and the discussion have established the fact that the increase in cost of the power house equipment consequent upon the suggested reduction in frequency is far more than offset by the reduction in cost of electric equipment of rolling stock consequent upon the adoption of 15 cycles.

During the discussion of Mr. Sprague's paper presented on May 21, 1907, announcement was made of a new motor which it was claimed performed so well at 25 cycles that the argument in favor of 15 cycles for heavy railway work was materially weakened. The motor referred to was that which has been disclosed this evening by its inventor.

In Mr. Alexanderson's paper little is stated relatively to performance of the new motor at frequencies lower than 25 cycles per second beyond the statement in reference to its commutation that it, " is equally well applicable to 15 or 25 cycles ", and that " it can, therefore, be stated in general that 25 cycles is entirely satisfactory for all geared motor work; it is preferable in that the combination of motor and transformer weighs less at 25 than at 15 cycles ". Regarding the statement that the commutation is equally good at 25 or 15 cycles, it is to be regretted that the author does not show in Fig. 7 the curve of the electromotive force of alternation short circuited by brushes when the motor is operated at 15 cycles. It is obvious that commutation at 15 cycles will be improved, and there is no reason suggested why this improvement, expressed in percentage, should not be as great in the case of this motor as in that of the series compensated motor. In the second statement quoted, one of the principal advantages of the lower frequency is entirely ignored. The relative aggregate weight of motor and transformer is unquestionably important, particularly in multiple unit work; but much more important, at least in the field of heavy electric traction, is the power of the motor that can be placed in a given space on the truck. The factor of cost is also against the 25-cycle motor. From the facts given, I believe that this new motor will gain as much in ratio of output to weight at a given speed by reduction of frequency from 25 to 15 cycles, as will the series compensated motor.

It seems to be a fair generalization to say that alternating-current motors having speed characteristics resembling those of the direct-current series motor will gain approximately 30% in torque, and will also gain materially in sustained power by reducing the frequency from 25 to 15 cycles per second. I find nothing in Mr. Alexanderson's paper to indicate that this motor is an exception to the general rule. If I have not understood it I shall be most happy to be corrected, as no one can question the weight of the arguments against the adoption of a new standard frequency and such adoption can be justified only by the existence of controlling considerations such as those to which I have referred.

B. G. Lamme: This paper describes a certain type of single-phase commutating motor, and comparison is made with the series compensated type, generally to the apparent disadvantage of the latter. It is intimated that this motor does what the series compensated motor cannot do. The theme of the paper appears to be that successful commutation of alternating currents has at last been obtained. Instead of accepting these conclusions, I am free to state that I do not see that this motor does, or can accomplish more than has already been accomplished successfully by a properly designed series compensating motor. Further, I claim that the series compensated type, as already built, is in certain features so far ahead of the type described in this paper, that it looks like exaggeration when a comparison is made in figures. In this paper, describing what is claimed to be a new and superior type of motor, no characteristic curves or data are given, and consequently no quantitative comparison can be made with other designs.

Let us first consider the starting conditions and characteristics. The general scheme of starting is based on the use of a relatively weak field at the beginning, the field induction being increased, for the same torque, after sufficient speed has been attained to make the commutating poles effective. Theoretically, assuming no saturation of the magnetic circuit, this increase in induction could be approximately 41 per cent, but practically it would be but 20 to 30 per cent., the material in the machine being worked economically. The object of this relatively weaker field at start is to lower the voltage in the coils short-circuited by the brushes. Referring to commutating motors in general, the author says:

> The sparking at start is quite insignificant, up to a certain value of the voltage short-circuited by the brush, but beyond this point the commutation rapidly becomes worse.

The author admits that it is either necessary to keep below this critical voltage, or to use preventive leads. This is the parting of the ways. It is either necessary to limit the design of the motor to such proportions that the induction at start can be kept down to such a low value that the short-circuit voltage is below the critical point, or, to take a broader course, to use preventive devices and thus raise the critical point and increase the output and improve the performance. Apparently the author does not believe that preventive leads, or resistance leads as he calls them, permit sufficient increase in the short-circuit voltage to represent any great gain in the operation. I disagree with him here, and will give some figures which I think will bear out my point of view. I am going to compare this arrangement with the series compensated type by assuming both to be applied to a motor corresponding to the present New Haven locomotive motors, which have a normal rating of 250 h.p. at 220 rev. per min. at 25 cycles.

This size of motor is selected for comparison, principally because I have more data of various combinations of windings of armature and field, than on any other large motor. In bringing through the first New Haven motors numerous arrangements were tested, such as fields with under- and over-compensation, commutating poles, etc., and armatures wound with and also without preventive leads. The combination giving the best all-round results is that used on the New Haven equipments.

These New Haven motors are worked at the time of starting at a high induction per pole, and in consequence at a high short-circuit voltage. Therefore, as this is a practical case it is fair to use it in making the comparison. But before making the direct comparison I shall digress slightly to take up the subject of currents flowing in the armature windings of single-phase commutator motors. Two currents should be considered: first, the working current which is fed into the brush and which passes into the commutator bars, through the connections, or leads, into the main armature winding; and secondly, a local or short-circuit current which passes from the short-circuited coil out through the lead or connection to one commutator bar, then through the brush to the adjacent bar and back through the lead to the coil. This local current is dependent upon the voltage generated in the short-circuited coil and upon the impedance in the closed circuit. If this local current could be limited to values approximately the same as the working current in the coils, then it could be taken care of very readily by the ordinary resistance of the brush, brush contact, etc., but unfortunately a short-circuit voltage low enough to give this condition would give absurd proportions in the motor. In order to obtain a reasonable capacity from these single-phase motors, it is necessary to work at an induction giving a short-circuit voltage so high that this local current would usually be many times greater than the normal working current in the coils. It is for the purpose of reducing this short-circuit current to a more moderate value, that preventive leads are added. It has been assumed that the addition of these leads means an increase in loss. However, as the purpose of the leads is actually to reduce the excessive local current, the result is a very considerable decrease in loss by the use of these leads. The following figures will indicate wherein these leads are beneficial.

Taking up again the comparison which I proposed to make, let us consider that, with either scheme of winding, the motor starts under double normal full load or one-hour torque. This condition occurs very frequently in the operation of the New Haven equipments, and is even very considerably exceeded at times. Under this condition of double torque, the motor with the series compensated winding has an induction of approximately 1.25 times normal and a working current in the armature and field of approximately 1.6 times normal or one-hour current. The preventive leads are so proportioned that the local or short-circuit current at this overload torque is, roughly, about 1.25 times the normal working current in the armature conductors. Next, applying the scheme described in Mr. Alexanderson's paper in order to get twice full-load torque, the field would have normal full-load induction and the armature would have double normal current, compared with a field of 1.25 and an armature current of 1.6 in the compensated series motor with preventive leads. This double current in the armature with normal field strength would not look so bad if it were possible actually to operate satisfactorily under this condition without preventive leads. But with the high normal induction per pole on the New Haven motors, the tests show that it is utterly impracticable to start with normal induction in the field without preventive leads in the armature, for the short-circuit or local current is excessive and causes vicious and destructive sparking. Our data indicates that, without preventive leads, and using brushes of medium low resistance, such as are used in ordinary generators and motors, this New Haven motor will give a short-circuit of about seven times normal working current in the coils with normal full-load induction in the field. This condition is prohibitive and is far beyond the critical point mentioned before. Even reducing this induction to 70 per cent. of its normal value, the short-circuit current is still about five times normal current, which I consider to be too high. However, let us assume this value. The field strength at double torque would, therefore, become 0.7 instead of normal, and the armature current for the double torque would have to be increased to 2.86 times normal instead of double. The current with this arrangement would then be as follows:

Short-circuit approximately 5 times normal.
Working current 2.86 times normal.

These should be compared with the compensated series arrangement in which these values are:

Short-circuit 1.25 times normal.
Working current 1.6 times normal.

The total current required by the brushes and commutator in the compensated series motor would therefore be approximately one-third that required if the scheme described in this paper were used. Let us carry this analysis a little further. Assuming that we could start satisfactorily with the 0.7 normal induction indicated above, then when speed is attained a 40 per cent. stronger field could only be obtained provided there were no saturation in the magnetic circuit. But taking saturation into account, the increased induction would hardly be 30%. It is evident, therefore, that in order to accommodate the starting conditions the normal induction must be sacrificed somewhat; and with the highest permissible field at start the normal induction would be considerably lower than if preventive leads were used. Another interesting point to be noted in these figures is the comparison of relative inductions at start with the two arrangements. It may be seen that the motor with preventive leads shows 1.25 times normal induction, while the method proposed in this paper shows 0.7 normal. The gain in induction by the use of preventive leads in this case is approximately 75%, and even with this increase in induction I am confident that this motor would make the better showing as regards sparking and burning at the commutator and brushes during starting, due to the greatly reduced local currents. The above figures also indicate clearly the disadvantage of trying to improve this condition by the use of high-resistance brushes. Necessarily the life of such brushes would as indicated be considerably shortened by the excessive currents.

This method of considering the currents flowing in the armature shows very clearly why 15 cycles is more advantageous than 25 cycles in the alternating-current commutating motor. As the short-circuit voltage is a direct function of the frequency, as well as of the induction, it is evident that with the same limiting short-circuit voltage the induction could be increased in the ratio of 25 to 15, or 66%. It is evident, therefore, that the limit of induction at start is thus raised enormously. In practice, however, unless the motor is worked at extremely low saturation, the full gain of 66% can not be obtained either at start or at speed; for in order to obtain the greatest economy in weight and dimensions, it would be natural to work the material at as high saturation as permissible, and in practice there would be only about 30% gain. As we could work 66% higher with the same short-circuit voltage, this increase of only 30% means that the short-circuit voltage is thus less than 80% that of the 25-cycle motor of corresponding design. There is thus about 30% greater output due to the higher induction, and at the same time this is obtained with a lower short-circuit voltage and therefore with more favorable starting conditions.

I have expanded on this starting condition, for experience with large motors shows that it is a most difficult one to meet in locomotive work. Also, tests indicate that the local or short-circuit current is a maximum at start, being close to the theoretical value, but falls off rapidly as the machine speeds up.

Mr. Alexanderson intimates that even if the losses are excessive in the armature winding at start, yet the quick starting and acceleration will greatly reduce the danger from this source. This may be true of small equipments where light torques are required, and quick acceleration always possible; for heavy work, however, there are many occasions where it is necessary to start very slowly and run slowly for a considerable time. I shall cite some of the tests made with the locomotive equipped with two 500-h.p. motors and exhibited at Atlantic City at the Street Railway Convention last October. This machine was given some very severe tests last summer at East Pittsburg, in the presence of prominent railroad engineers. In some of these tests the locomotive was operated for five minutes at speeds of from two to three miles per hour, and this while exerting more than double torque. This represents less than one-tenth the normal or rated speed of the motor. The motor was also held at standstill for considerable periods, developing excessive torques in attempting to start trains with the brakes set. Under this condition, a motor without preventive leads would, unquestionably, have been ruined. This condition of the motors at standstill, with a heavy current flowing, is particularly liable to be met with in freight service, especially if two or more locomotives are working independently with a very heavy train. It will be impracticable to start all the locomotives at the same instant, as they may be in different parts of the train; consequently, one locomotive may develop a high tractive effort at standstill for some little time before the other locomotives are thrown in. To meet such conditions in practice requires a motor that can be held at standstill for more than an instant when developing heavy torque. It has been claimed by some engineers that under this condition the preventive leads, or resistance leads as they are called, must necessarily burn out, because they have a large loss in them at this time. It is under this very condition that the motor with the preventive leads shows to great advantage over the one with excessive short-circuit currents, and without such leads. As mentioned above, this explains why the latter type of motor is liable to be injured during a failure to start; it will not do simply to say that on account of rapid start and quick acceleration the motor will not be injured. In freight service, the opposite condition of starting must be handled with certainty.

It may be said that Mr. Alexanderson's motor is a true commutating-pole type of machine, but instead of using a separate pole placed in the interpolar gap the two edges of the main pole are used as an interpole. This may be illustrated by the following diagrams.

In Fig. 1 is shown the ordinary arrangement of winding with an interpole, the winding being the full pitch. In Fig. 2 the interpole is shown at one side. In Fig. 3 the pitch of the coils is shortened and the interpole is widened a corresponding amount so that this pole still covers the armature coils. The pitch is narrowed until the two sides of the coil lie under the two edges of the main pole. The width of the interpole is therefore such that it would overlap the main poles, if superimposed. It is evident that the centre of this interpole is useless and could be cut away as shown in Fig. 4. As this pole overlaps the main poles in position, it is evident that the edges of the main poles themselves could be used as interpoles if the winding surrounding the interpoles is properly placed in the main poles so as to surround these two edges. This is just what the compensating winding does. The effect, therefore, is the same as if interpoles were used, for part of the main pole were converted into an inte pole, as shown in Fig. 5. However since it is evident that part of the main pole is converted into an interpole, it is also evident that part of the main pole, used as an interpole, represents that much loss in the effectiveness of the main pole. In other words, the armature coil does not surround all the induction from the main poles, but only part of it, and in consequence of this reduced effective induction the counter electromotive force of the machine is reduced. Another way of putting it is that the effect is the same as reducing the number of armature turns. In order to bring the effective induction of the main poles up to the required value, more exciting ampere-turns are required. This means that the power-factor of the machine is lowered somewhat by this arrangement.

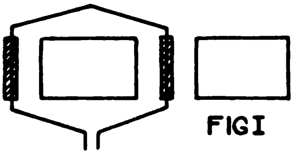

FIG I

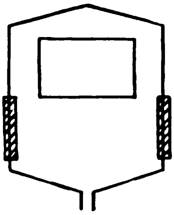

FIG II

In these single-phase motors the object is to get the polar area as large as possible, so that with a given total induction per pole the excitation, or exciting ampere-turns, may be as low as possible. This insures a high power-factor. In Mr. Alexanderson's motor this condition seems to be departed from considerably. In the Siemens-Schuckert motor the commutating pole is placed in the interpolar gap and excited in shunt with the main circuit. This arrangement gives the benefit of the full pitch winding and the effective polar area is relatively high, possibly 15% higher than in the motor described in this paper. In the motor designed by me the polar area is relatively a little less than in the Siemens-Schuckert, possibly from 3 to 5 per cent.

In reference to frequency, the author says broadly, but without argument, that there is little or no field for the 15-cycle motor. The only basis for this statement is apparently that good commutation is now possible at 25 cycles. In the discussion of the paper by Messrs. Stillwell and Putnam last January, it was not the question of commutation which was advanced as the reason for the adoption of 15 cycles, for it was stated plainly that 25-cycle motors could be made to commutate well. The greatly increased ratio of output to dimensions was given as the principal reason for the adoption of the lower frequency. I see absolutely nothing in this paper to change that conclusion. The motor described this evening, if properly designed, should show just as much improvement at 15 cycles as the series compensated motor; for, as explained before, the use of a lower frequency will allow about 30 per cent. increased induction. In fact, this motor, being worked at a relatively lower induction at start than

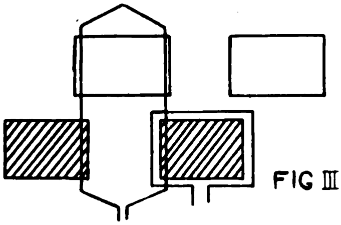
FIG III

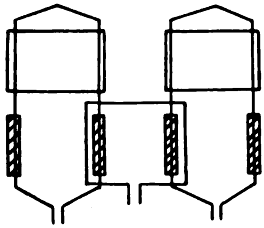
FIG IV

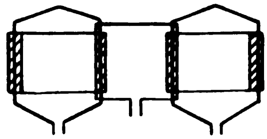
FIG V

the series compensated type, and therefore at less saturation, should show a relatively greater per cent. gain at 15 cycles as regards starting, and should also show practically the same per cent. gain as the compensated type, when at speed. Of course this is not on the basis of simply taking a given motor built for 25 cycles and operating it on 15 cycles, which will show a small gain. But the excitation, or exciting ampere-turns, must be increased and this can be done at the lower frequency without reducing the power-factor; for the inductive volts across the field winding are a function of the frequency as well as of the induction, and thus any reduction in frequency will permit an increase in the induction of the motor. A 30 per cent. increase in the induction of such a motor means a 30 per cent. increase in the counter electromotive force of the armature; and with the same current flowing, the output and the torque are increased at least in proportion to the field strength. It is in this feature of increased induction that the principal gain with lower frequency is to be found. This increased induction is obtained with less short-circuiting in the armature and also with less exciting voltage in proportion to the counter electromotive force, and consequently with higher power-factor. If it were possible to design a 25-cycle motor of large capacity and moderate speed, so that it could be worked at high saturation, then there would not be so much gain in weight and cost by the use of lower frequency, for extra material would have to be added to the magnetic circuit when the induction is increased. But on the larger sizes of 25-cycle motors the iron cannot be worked to high saturations because it is not permissible to put in excitations sufficient to saturate the motor. In fact, it is in general difficult, in such motors, to get in enough excitation for the air-gap alone, unless the field volts are made undesirably high, thus lowering the power-factor. In consequence, on large, moderate-speed, single-phase, 25-cycle motors there is a strong temptation unduly to reduce the air-gap in order to keep down the excitation and thus decrease the size of the motor. In the 15-cycle motor on the contrary, a considerably larger air-gap can be used than on 25 cycles, due to the fact that there is much more margin for excitation without reducing the power-factor below desirable limits.

If the commutation at speed were the only limit in the 25-cycle motor, then it would be correct to say that with this limit raised sufficiently there would be no necessity for the lower frequency, but as the present limits in design of large 25-cycle motors lie in the excitation permissible with good power-factor, and in the short-circuit voltage at start, it does not seem to me that the problem is solved by simply applying a different method of obtaining commutation when running. The real limits which affect capacity still remain, and I do not see wherein the motor described this evening changes the broad problem in any way. I believe that if Mr. Alexanderson continues his investigations, especially with large motors for heavy railway service, he will be forced to the same conclusions.

W. B. Potter: The single-phase motor described by Mr. Alexanderson possesses a number of novel features, but the essence of the improvement is the better inherent commutation. Because of better inherent commutation it is possible to modify the other features affecting the performance of the motors which have heretofore been subordinate to commutation, with the natural result of greater reliability, decreased maintenance, and greater capacity for a given amount of active material.

It is very desirable that the motor equipment of a motor car should be able to develop sufficient torque to slip the driving wheels; for an electric locomotive this is particularly desirable.

Mr. Lamme questions whether a single-phase series repulsion motor will have an output equal to that of a series motor. I call his attention to a recent test of a series repulsion motor having the same armature dimensions and number of poles as the series motor on the New Haven locomotives to which Mr. Lamme refers. I understand that this New Haven motor has a limiting tractive effort of about 5000 lb. The series repulsion motor on the basis of the same diameter of driving wheels gives a tractive effort in starting of 7500 lb. and good commutation up to 75 miles per hour.

An electric locomotive is figuratively, a draft horse, and its value as such is proportional to the weight on the drivers. In whatever degree the draw-bar pull is limited by the motors, the value of the locomotive, as a tractive machine, is decreased to the same extent. In the handling of any service, sufficient draw-bar pull to start a train is absolutely essential, the horse-power rating for maintaining the schedule being subordinate and depending upon the degree of continuous service. As affecting reliability, the motors are liable to injury from overload unless the load is limited by the slipping of the wheels rather than by the commutation or current capacity of the motors.

With any probable design of motor car or locomotive, the geared series repulsion motor will be able to slip the wheels even if geared for maximum speeds as high as 75 miles per hour. In the light of present knowledge, the problem is somewhat more difficult with the gearless series repulsion motor. With respect to the torque of the gearless motor, the state of the art to-day is not unlike that associated with the geared motor about two years ago.

In the many problems that arise in electric traction, a liberal discount may well be allowed for improvement. For those concerned in development and design, progress in new and untried fields is a privilege and duty, but for those interested only in the earning capacity a conservative attitude will usually best insure economic results. I would not counsel undue caution, but even with the radical improvements which have been made in the single-phase motor, it does not yet follow that single-phase traction is properly applicable to all conditions. A knowledge of the art of compromise constitutes the basis of most of our work, but the equations to be considered are lacking in their most essential feature if they do not contain the $ sign as applied to each particular problem.

O. S. Lyford, Jr.: Many of us thought the repulsion motor dead, and we rather hoped it would stay dead, not that we had anything particular against that type of motor, but because we are beginning to get acquainted with the series single-phase motor which is serving us well. I should like to see one type perfected rather than two or more. If, however, the development of the motor which Mr. Alexanderson has described means a reduction in the cost of single-phase equipment, it will be welcome, as the price of such equipment is now certainly close to the prohibitive limit.

W. I. Slichter: The motor described has so many new features in its make-up that it is rather perplexing to grasp the principle of its action as a whole. It may be of interest to discuss these features separately and from a slightly different point of view from that taken by Mr. Alexanderson. In explaining the motor it is necessary to consider the conditions of starting and running separately, as certain features are introduced simply to assist in starting and other features are employed only to function when running.

Starting. In all single-phase commutator motors there is a definite value of the flux per pole above which it is indavisable to operate since the electromotive force of transformation in the short-circuited coil undergoing commutation becomes so great as to give unsatisfactory commutation. This limitation is particularly strict at starting, when the armature is at rest or moving very slowly. As the motor speeds up it would be possible to use a higher flux value; first, because each coil is under the brush a shorter period; secondly because there are various means of counteracting the electromotive force of transformation by devices dependent upon the speed of the armature.

But in all series type motors the natural characteristics involve a decrease in current with increasing speed, and hence a decrease in flux. If, therefore, a motor is designed with a proper value of flux at starting, it will have too little flux at running; if with a proper value at running conditions, it will have too great a flux and bad commutation at starting. This limitation does not prevail in direct-current motors, since any value of flux may be used without harmful effect.

In the motor under discussion, the compensating or inducing winding and its inductive relation to the armature turns are made to act as a series transformer. By winding the compensating winding with twice the number of turns as are on the armature, there will be twice as much current in the rotor as in the stator when the rotor is short-circuited, and the same current in both members when the rotor is open-circuited. This gives an approximation of the ideal conditions in a single-phase commutator motor—that of operating at all speeds with the strongest field compatible with good commutation.

Running. Under running conditions we find in this motor three very important new features contributing to good operation.

1. The proper field strength at all speeds, as just mentioned.
2. By means of a fractional pitch in the armature (Fig. 1), the coil undergoing commutation is placed in a position under the pole piece, where it is very strongly influenced by any magnetomotive forces in the compensating winding, so that the latter winding is able to act as a real commutating pole as well as a compensating winding.
3. The compensating winding is made to carry two components of current—a series current and a shunt, or repulsion motor current. It may be likened to a commutating pole having two coils, one a series coil serving very effectively, due to the favorable position of the coil undergoing commutation (brought about by the fractional pitch), to produce the good effects on commutation that a commutating pole does in a direct-current motor; in other words, to correct for the harmful electromotive forces of self-induction and armature reaction. This is accomplished by making the compensating winding stronger than the armature winding, thus the excess of compensating winding magnetomotive force sets up a local flux at the corners or tips of the poles which becomes a commutating pole.

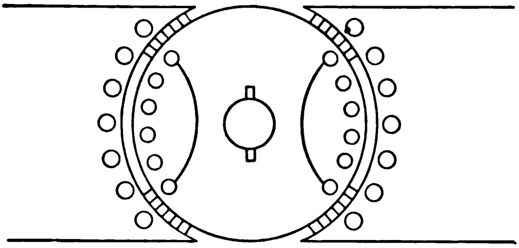

FIG. 1.

The shunt coil, shunt component of current or repulsion motor current, corrects or reduces the electromotive force due to transformer action in the coil undergoing commutation by a happy combination of phase relations, as shown by the following vector diagram, (Fig. 2).

E_0 is the line or terminal voltage of the motor.

I_0 is the series-load current of the motor lagging behind E_0 a small amount, as in normal running conditions.

ϕ_m and ϕ_c show the time-phase-position of the two fluxes, motor and compensating, produced by I_0. These have different space-positions.

e shows the harmful electromagnetic force of transformation in the short-circuited coil, 90° behind ϕ_m, because ϕ_m produces it by induction.

A portion of E_0 is now impressed across the compensating winding in shunt, producing a flux ϕ_1 90° behind E_0. But the compensating winding is wound opposed, or 180°, to the armature winding which throws this flux down to ϕ_2.

The armature coil moving in this flux has generated in it by rotation an electromotive force, e_2, in phase with ϕ_2 which is approximately opposed to e, combines with e to make the resultant e_3, which is of very small magnitude and of such phase as to be subject to the corrective influence of the flux ϕ_c of the ordinary compensating winding.

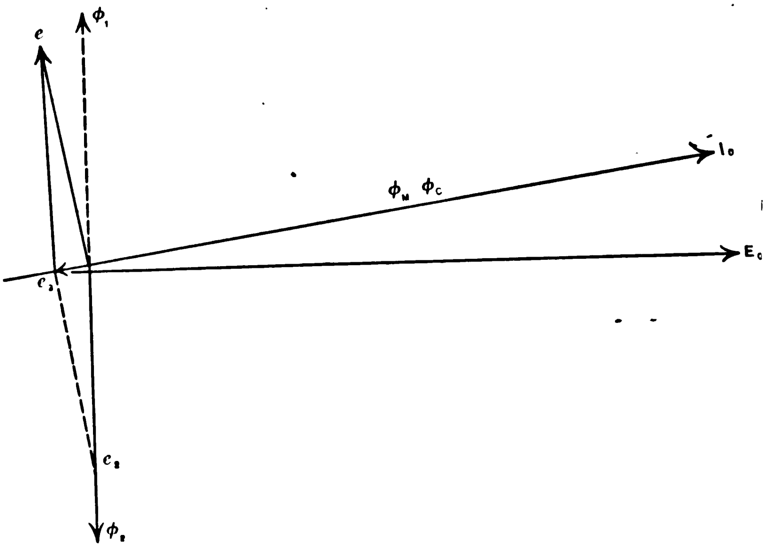

FIG. 2

The final result is that the commutation troubles of the single-phase commutator motor are corrected in the logical way of removing the cause instead of the half-hearted way of reducing the effect, as is done with high-resistance leads.

A certain number of wattless volt-amperes are consumed in producing this effect, but a considerable amount of energy is saved and removed from a place which is particularly sensitive, the commutator, and a very large saving is effected in maintenance.

One of the immediate results of the development of this motor is the fact that it makes the need of 15 cycles for single-phase railway work a great deal less important than with either the plain repulsion motor or the plain series motor. As brought out in the discussion of Messrs. Stillwell and Putnam's paper, the greatly increased cost of generators and transformers at 15 cycles is a considerable handicap to that frequency, and with the former types of motors a 15-cycle system showed a lesser cost only in very heavy work where a large number of heavy motors were required. With the new motor, a considerable portion of the field of the 15-cycle motor has been conquered, and although the new motor is slightly better at 15 cycles than at 25 cycles, it will probably be found that there are very few cases where any 15-cycle motor and its transformer will weigh or cost as little as this type of motor and transformer at 25 cycles.

In the control of this type of motor it will be noted that the sequence of steps is very simple, and that each contactor handles only one half the maximum current used, thus the switches or contactors will be reduced in size and number and the equipment made considerably lighter. Also, due to the fact that the terminal voltage of the motor is higher, there is a saving in the weight of the car compensator or auto-transformer.

Mr. Alexanderson's scheme of using a fractional pitch winding on the armature overcomes the principal objection that was found in the use of the repulsion motor in this country. The objection being that the simple repulsion motor does not operate satisfactorily on direct current, due to the fact that with a full-pitch winding commutation would take place in a field unfavorable to commutation, since the neutral space is necessarily restricted in this type of motor.

To be successful in this country, any single-phase motor must be capable of operating over the existing direct-current systems. This gave the series compensated motor an advantage over the repulsion motor for interurban work, but with the motor under discussion to-night, this difficulty is removed. We have developed a repulsion motor which operates perfectly satisfactorily on direct current.

S. M. Kintner: I am disappointed because Mr. Alexanderson has not told us more about the behavior of the motors in actual service. The theory is nicely worked out, but I for one would be better satisfied with less theory and more matter of a quantitative nature. For instance:

1. What is its power-factor?
2. How does it compare in weight with standard direct-current motors of equal torque?
3. How does its commutator wear in service requiring frequent acceleration with large torque and corresponding heavy currents?
4. What character of brush is used, and what life in car-miles is obtained?
5. How long can it stand locked with 150% full-load torque?
6. How does it stand sustained overload torques of 150 per

cent.—200 per cent. of the hour ratings, for periods of 3 or 4 minutes, when operating at normal speed and also at very low speeds.

The above conditions are the critical ones in the operation of single-phase motors, and it is upon their ability to stand such tests and service that their value should be based. Mr. Alexanderson's commutating-pole motor will probably give good commutation when running, but so will any well-designed series compensated motor with preventive leads. It is not the running but the starting condition that is the troublesome one; it is then that motors with preventive leads show their greatest superiority over those without them. The proposed method of obtaining improved running commutation is of questionable value when it is obtained, as Mr. Lamme has pointed out, at the sacrifice of starting torque and power-factor or by increase of motor weight.

The power-factors of a certain line of series compensated motor, with which I am familiar have the following values:

Twenty-five cycle motors, varying in size from 75 to 250 h.p. at their hour ratings, power-factor = 85% to 90%.

Fifteen cycle motors, varying from 75 to 500 h.p. power-factor = 88% to 94%. Some of these 15-cycle motors are simply 25-cycle motors adapted to the 15-cycle service. All of these values are taken from motors having reasonable speeds and good commercial air-gaps.

Data on weights on those same motors show that in comparison with the standard line of direct-current motors on a basis of percentage weights for equal torques, the 25-cycle motors weigh 33 per cent. more, while the 15-cycle motors weigh 10 per cent. more. The weights in all these are total-motor weights, including gears and gear-cases.

In checking over these values a noticeable point was the limitations that the 25-cycle motors were reaching; for the larger size motors the percentage weights were increasing quite rapidly. This was not noticeable within the limits checked on the 15-cycle motors. This limit in the 25-cycle motor is caused largely by the increase in iron necessary to keep down the inductive element and consequently secure a reasonable power-factor.

Recent calculations show that in a given space it is possible to get a 500-h.p. motor on 15 cycles, but the best that could be designed for equally good performance on 25 cycles was 360 h.p. From this it is evident that 39 per cent. greater output is possible in the same space with 15 cycles. This indicates very clearly the need of 15 cycles for the heavier class of service.

The motor described by Mr. Alexanderson is limited in precisely the same manner as the series compensated type, and at smaller ratings. It will also be benefited, so far as output for a given weight is concerned, by the use of 15 cycles.

In dismissing the question of 15 cycles, Mr. Alexanderson admits that for large gearless motors for high-speed service there is an exception. Why except this class of service? Is commutator speed the reason?

A comparison of two 4-motor equipments made up of 75-h.p. motors at 25 cycles and the same motors adapted for 15 cycles giving 95 h.p., shows very clearly the gain in tractive effort and horse power possible with the 15-cycle motors. The total electrical apparatus per car was but 5 per cent. heavier with the 15 cycles but the gain in horse power was 26 per cent. On a basis of total car-weights, the difference were 1.6% increase in weight on 15 cycles and a gain of 26 per cent. in horse power.

The commutator wear in service requiring frequent and rapid acceleration is a serious one. A commutator that will not take a gloss, will rapidly consume brushes and soon go to pieces. If the currents are heavy at starting, and the starting frequent, the commutator is apt to have copper drawn from bar to bar and thus short-circuit certain coils. To show the limitations of a motor of this character a test should be conducted as follows: the motor should be mounted on a shaft driving large fly-wheels, the inertia of which corresponds to that of heavy cars accelerating from rest. The control should be arranged so that as the wheels are accelerated the proper sequence of switch operations and voltages are applied to the motor. When a predetermined speed is reached, the power is cut off and the motor allowed to coast for a fixed time, when brakes are applied and the wheels brought to rest. This same cycle is repeated automatically by a motor-driven control, the single-phase driving motor thus being subjected to a service more severe than any it is apt to meet in operation on a car. This is an excellent test of the motor's ability to stand heavy currents while at rest, also while accelerating slowly, as it is connected rigidly to the shaft and gets the full force of the first rush of current.

This test should be continued for a week or more. The current used should be much in excess of the motor's ratings, and forced air will be necessary to keep down the temperatures to safe limits. The test is not one of temperature, but one of commutation under abnormal service conditions.

This test is also quite effective in determining carbon-brush characteristics. Within the last few days I have compiled some data gathered from a road operating approximately 100 motors of this kind, each of 100-h.p. capacity. This road reports the car-miles per brush as follows:

October	November	December	Average
14,600	15,550	15,450	15,200

The motors from which these data were taken are in a very hard service, the cars averaging over 200 miles per day. On one run the car is compelled to make 583 miles per day. During October one car ran 10,740 miles; during November, 9,400 miles. Another road using similar motors reports approximately 13,000 car-miles per brush as the average for the last two months.

These motors have all been in operation over a year and have brushes of a medium grade, such as are used on direct-current motors and generators.

☛The ability of motors with preventive leads to stand excessive overload torques when locked for periods of 10 or 15 seconds has been demonstrated repeatedly by testing them after being on cars or installed on locomotives. These tests have been made by applying power with the brakes locked, and at other times by attempting to pull trains upon which the brakes were not released. The requirements of overload are largely at starting; they are not so important when running. During the last year and a half I have followed closely the operation of about 600 of these motors; I do not recall a single case of trouble that could be traced to a preventive lead burning out.

While many may look upon preventive leads as a luxury, in my opinion they supply the most economical design possible with single-phase motors in the present state of the art, I believe that they will continue to be used until some one devises a motor that is not subject to the short-circuit action in starting, as well as in running. Mr. Alexanderson's motor does not fulfil this requirement, and I see no reason why it could not be improved by adding preventive leads.

Mr. Potter says that with the Alexanderson motor it is feasible with motors of the same dimensions to get 50 per cent. more tractive effort than that of the New Haven motors. My opinion is, that so long as the torque of motors depends upon the number of conductors on the armature, the limits of which are determined, by the size of commutator with reasonable barwidth, secondly, upon the induction per pole which is admittedly lower than that in the New Haven motor, and, finally upon current, that it can not be done with reasonable currents for the possible size of commutator.

Chas. P. Steinmetz: It is true and has been well known since the early days of electrical engineering, that any direct-current motor can operate on alternating current, if its magnetic field is laminated so as to be responsive without excessive loss to rapid alternations of magnetism. But there were two great objections to this motor, both well recognized in the art before any extensive work was done; these objections were impracticably low power-factor and hopelessly bad commutation. I remember reading as far back as 1889 in Mr. Gisbert Kapp's at that time classic booklet on alternating-current machinery, the proof, that the single-phase alternating-current motor can never be of any practical use, because its power-factor must be too low for practical use. The first problem that had to be solved in getting an operative motor, was to raise the power-factor to practical values. This was undertaken and solved about eighteen years ago by Rudolf Eickemeyer, who gave us the compensating winding, which now is used in all single-phase alternating-current motors. He recognized, that to give a good power-factor, the single-phase commutator motor must have few field turns, many armature turns; that is, a weak field with a strong armature. To be able to use these proportions, the armature reaction and self-induction must be neutralized by a compensating winding; a coil surrounding the armature as closely as possible and energized either by the main current in series and in opposite direction to the armature current, or closed upon itself and energized by its secondary induced current. Eickemeyer gave us both types of operative alternating-current commutator motors, the conductively compensated, and the inductively compensated. Thirteen years elapsed before the electrical industry caught up with Mr. Eickemeyer's work, and the compensated series motor was applied to commercial service.

Independent thereof, and starting even earlier, an apparently entirely different type of motor was experimented upon and designed by Elihu Thomson. This was the so-called repulsion motor. On converging lines these two motors have continued throughout the intervening period, until now in Mr. Alexanderson's series repulsion motor they merge into one. Mr. Alexanderson's motor is not a compromise between the two types of motors, but a modification of the repulsion motor so as to give at all speeds, the perfect commutation that the repulsion motor has only at synchronous speed; that is, perfect commutation at all speeds by producing the condition of synchronous commutation at any desired speed.

After Mr. Eickemeyer's work was concluded, and the compensated series motor had arrived, there remained the problem of commutation, which has been the great problem of the alternating-current railway motor during the last few years, although frequently it has been more or less hidden under statements regarding size, weight, etc. Looking into the design of the compensated series motor, it will be found that there is no other inherent reason why it should essentially differ in weight or size or capacity from the direct-current motor, if it were not for the severe limitations in the design imposed by the problem of making the commutation sufficiently good not to be self-destructive in too short a time. The problem of getting reasonably fair commutation means that the alternating-current motor has to be designed with eight or twelve poles, where the direct-current motor would have four or six poles. It means that the alternating-current motor has to be supplied with a very large commutator to receive current at 150 or 200 volts, while the direct-current motor commutates much smaller currents at 500 and 600 volts. It is as easy to insulate 600 volts alternating current as 600 volts direct current, and so nobody would choose such large low-voltage currents and bulky commutators if not forced to it by the problem of commutation. So weight and size must be sacrificed to get moderately reasonable commutation. Some advantage is gained by the introduction of high resistance or high inductance leads. It must be realized, however, that the high resistance or high inductance leads, suggest, in a measure, the old saying, " Out of the frying pan into the fire ". Reducing the short-circuit current by interposing resistance or inductance, results in a drop of potential across the resistance or inductance, which appears at the edge of the brush when the brush leaves the commutator segment, so sparking can not be entirely stopped by this means. The logical way to improve commutation is to remove the cause of sparking, the short-circuit current under the brush.

Some years ago one of my assistants, Mr. Milch, investigated the short-circuit current under the brushes, and found that it could be eliminated by impressing a commutating field upon the motor at the commutation point, or in quadrature with the main field. By giving the compensating winding more ampere-turns than the armature, or by using a series commutating pole or an interpole arrangement that works successfully in the direct-current motor—the commutation of the single-phase alternating-current motor cannot be improved, because the alternating current has an intensity as well as a phase, and the magnetic flux of the inter-pole being in phase with the main flux and main current, is wrong in phase. A commutating flux is necessary; a flux that differs in phase from the main flux, and is approximately in quadrature therewith. The production of such a magnetic flux, or a true commutating flux, varying with the speed in the proper manner and differing in phase from the main flux, is what makes this series repulsion motor commutate perfectly at all speeds.

Another valuable feature of Mr. Alexanderson's work is the investigation of the distribution of the magnetic field. It is not sufficient merely to have the two quadrature components of the magnetic field of proper intensity and proper phase; what is essential in commutation is not the total quadrature field, but the field at the point where the brushes stand. This fact made it necessary to investigate the local distribution of the magnetic field over the armature circumference. The result of this work then eliminated the question of commutation from the alternating-current single-phase motor at all speeds.

It is true that at standstill the short-circuit current is still there, and must always be there, except that it may be interchanged against voltage by inserting resistances or inductance. It must not be overlooked, however, that the harmful effect of the short-circuit current is a function of the product of the current and the time during which the current exists; in this respect a motor in which the short-circuit current practically disappears at extremely low speeds has the advantage over a motor in which the short-circuit current retains the same relative proportion to the main current throughout all the speeds up to the highest. I believe this feature is the explanation of the great difference between Mr. Lamme's theoretical conclusion and Mr. Alexanderson's practical experience on one and the same size of motor.

It appears to me, therefore, that the second and last serious problem of the alternating-current motor which still remained after Eickemeyers work, the problem of commutation, has finally been solved by the work recorded in the paper before us. The alternating-current single-phase motor is in practically as good a shape as the direct-current motor, and I may perhaps say that with this work the second period in the development of the alternating-current railway motor, the period of youth, is concluded.

W. S. Murray: It is better to eliminate the cause of, rather than remedy, a deleterious effect. Thus an arrangement which naturally produces a proper commutating flux without especially providing extra means for it (such as commutating poles) is certainly a most valuable point gained.

Again, the elimination of resistance leads on account of the elimination of the cause requiring them is a welcome characteristic. We are all aware of the advantages, in high powered electric locomotives, of gearless construction; we are likewise aware, in this form of construction, of the high ratio of weight on drivers to tractive effort developed with alternating-current motor construction. In consequence of this unfortunate relation, should the entire electric locomotive weight be on drivers, it is impossible to design the motor equipment of sufficient capacity to slip the wheels of the locomotive; and as the transformer action is a maximum at starting, unless the locomotive enigneer shuts off power promptly upon finding the locomotive incapable of moving its trailing load, the resistance leads will burn out.

Mr. Alexanderson gives the general superior characteristics of his motor over those of the repulsion type. Since the introduction of the series compensated motor, I had been under the impression that the repulsion type could hardly be considered a competitor, due to the bad operating characteristics above synchronous speed, as explained in Mr. Alexanderson's paper. This new type of series repulsion (which by the way might have its name reversed and be called repulsion-series, as it has to start before it runs) combining the good characteristics of the repulsion type for starting and the good characteristics of the series type for running, brings about a worthy competitor and lifts the mark of alternating current traction to a higher notch.

Alternating current no longer recognizes direct current as a competing agent in the transfer of power. Commercially, they are in limitation to each other in this respect from a unit point of view in the ratio of 1 to 10,000, and so even though low transmission losses by alternating-current transmission may compensate for increased costs of traction apparatus, with its attendant lower efficiencies and greater non-revenue weights, it is a welcome sight to observe the alternating current motor designer, not satisfied with this, but setting up for his model of accomplishment a motor the equal in every respect to its direct-current confrére.

The feature of producing double torque at starting by short-circuiting the armature and without increasing the line current is a characteristic that lends itself in much value to traction necessities. Although the point is not brought out, I assume that this arrangement, prescribes that the motor operates at half of what the speed would have been had the short-circuit not been applied to the armature. In this connection, it would be interesting to know what change of relation takes place between time and the temperature of the motor when developing double torque, also how the power-factor of this motor compares with that of the series compensator type for starting, and low-speed conditions.

It would be interesting further, to know how the weight per axle horse power, one hour rating compares with direct-current motors of the same size, also what the ratio of hour to continuous capacity prevail in this class of motor.

E. F. Alexanderson: In answer to Mr. Stillwell's question whether the increased capacity in changing from 25 to 15 cycles applies in the same rate to the series repulsion as to the series motor, it can be said that if the heating of the motor is the limitation, it does not apply; if the starting torque is the limitation, it does apply. In the case of a motor that can slip its wheels, the heating is the limitation; in that case, the 15- and 25-cycle motors have virtually the same output.

A direct-connected motor may be called upon to give higher torque than is practical to obtain on 25 cycles, and in this case the ratio holds.

I thoroughly appreciate Mr. Lamme's contention that resistance leads increase the torque of the series motor by allowing the increase of the flux which is one factor necessary to torque. The other factor is the current, and by changing the ratio of excitation the current can be increased more than the flux could be increased by the use of resistance leads. The motor gives double torque with normal flux, and double current and normal torque with 70% flux and 140% current. The cross-currents in the brush may seem excessive, but they do no harm.

On a 50-ton locomotive that has been in service for half a year, hauling trains of about 400 tons, the motor slips its wheels without damage to the commutator, although it has not the improved arrangement for starting referred to in this paper.

Mr. Lamme made particular reference to the New Haven motor with a rating of 250 h.p. at 220 rev. per min. for one hour. I am familiar with this motor, because I have designed a repulsion motor for the same purpose with the same outside dimensions. This motor has been tested and has an output of 280 h.p. continuously, and 350 h.p. for one hour at the speed indicated by Mr. Lamme. This increase from 250 to 350 h.p. at the hourly ratings of the two motors is fully as high as the increase claimed by changing from 25 to 15 cycles.

A higher output can be obtained from the series repulsion motor for the same reason as in the 15-cycle series motor, by working the iron to saturation. If the higher flux were obtained by increasing the field turns, the effect would be, as stated by Mr. Lamme, a decreased power-factor. The power-factor, however, does not depend upon the number of ampere-turns in the field, but upon the ratio between excitation and armature reaction. By abolishing the resistance leads and allowing more room for copper, the armature reaction can be increased simultaneously with the field excitation and without affecting the power-factor, and the increased output is gained by increased voltage as well as increased current.

Mr. Kintner gave some data on the wear of brushes, A number of equipments of this type have been in operation for some time, but I am sorry that I cannot give the ultimate life of brushes, because they have not yet worn out. Brushes that have been in service for 10,000 miles show a wear of $\frac{3}{16}$ in. and the brush looks like new, so that there is no other limitation to the life of the brush than the amount that it can be fed down in the holder. The commutator assumes a brown polish like that of a good direct-current motor.

Elmer A. Sperry (by letter): It seems to me, that Mr. Alexanderson's paper indicates an epoch-making advance in the art of railway-motor design. In connection with the remarks that have been made in reference to slipping versus non-slipping drivers, if I understood the remarks correctly, it was stated that the dead weight of the equipments for heavy traction work range so high that it is impossible to get motors with power enough to slip the drivers sustaining these weights. I take this theory of the locomotive to be almost revolutionary. I think there is no railroad superintendent who would consider a steam locomotive that could not easily slip her drivers as worth putting a fire into. I have been engaged for some years in designing and manufacturing locomotiyes for the most strenuous sort of work, and I remember reading a paper before this Institute about fifteen years ago, describing some aspects of these machines. I most cordially agree with Mr. Potter, that one of the most essential features and one which must not be neglected in the design of a successful electric locomotive, is that it should be possible at all times to slip the drivers, even under conditions of heavy sanding. In this connection it might be stated that if it is considered important for the steam locomotive, it is certainly doubly so for the electric locomotive, where slip is necessary as a preventive of excessive overloading of the motors; this is a consideration of importance to us, but a point that does not in the slightest affect our competitor, the steam locomotive.

Several years ago we started to build rack-rail locomotives, principally for mine haulage. Since that time we have installed several hundred miles of this equipment and new installations are going on constantly. Here there is no safety-valve for the electric motor, no slipping has been possible, and we have had no little difficulty in adapting motors to this service. They have had to be designed and re-designed until a successful machine of to-day is, in case of emergency, able to slip the drivers, including the pinions up out of the rack, without damage to the motor. Leaving the rack occurs at a point between 180% and 200% of draw-bar pull.

I would emphasize what I have said, and add a note of warning to the designing engieer: a locomotive that can not slip its drivers will not be able to stand in competition with one designed easily to accomplish this function.

E. F. Alexanderson (by letter): Regarding Mr. Lamme's remarks concerning the use of resistance leads, I would say that in the series motor the function of the resistance leads is dual; first, to assist in commutation, and secondly, to help in starting. In the series repulsion motor the problem of commutation has been solved and therefore the only field of usefulness for these leads would be at starting. If resistance leads were the only solution to obtain good starting, they would be used in the series repulsion motor, as series repulsion motor with resistance leads would give the same increase in rated capacities, and the same improvement in commutation, as would be effected by changing the frequency of the series motor from 25 cycles to 15 cycles.

The above statements are verified by actual tests. Messrs. Lamme and Storer have given examples before the Institute of tests which show that a 100 h.p., 25-cycle series motor when operated at 15 cycles is rated at 125 h.p. Other tests have been made on a 75 h.p. motor operating as a series repulsion motor at 25 cycles, and operating as a series motor at 15 cycles. The results of these tests show that the heating was lower in the former than in the latter instance. Another series repulsion motor of 450 h.p. continuous output, when running at 400 rev. per min. showed that the heating was only five degrees centigrade higher when operated on alternating current at 25 cycles than operated on direct current.

The characteristic curves given in Fig. 1 relate to the last named motor, and it may be of interest to state that this same machine has delivered 800 h.p. at 310 rev. per min. with almost sparkless commutation. An examination of the power-factor curve shows that its general nature varies somewhat from that of the series motor in being more constant through its entire range of operation, and it gives a speed curve more nearly resembling that of the direct-current motor than can be obtained with the series motor.

As this power-factor ranges from 90 to 94%, it certainly does not need to be apoligized for, as some the other speakers seem to think. If my remarks in the text of the paper are taken as apologetic, I must explain that I was comparing the power-factor of the series repulsion motor with that of the Latour-Winter-Eichberg motor, which at least is worthy of as much consideration as the series motor.

In answer to questions about the ability of the series repulsion motor to exert a torque at standstill, I reply that motors have been tested with the armatures blocked and have given double their normal torque for one minute. A large number of series repulsion motors are in operation without resistance leads, and no difficulty has been experienced in starting although these motors have not the improved features of starting which are referred to in the paper.

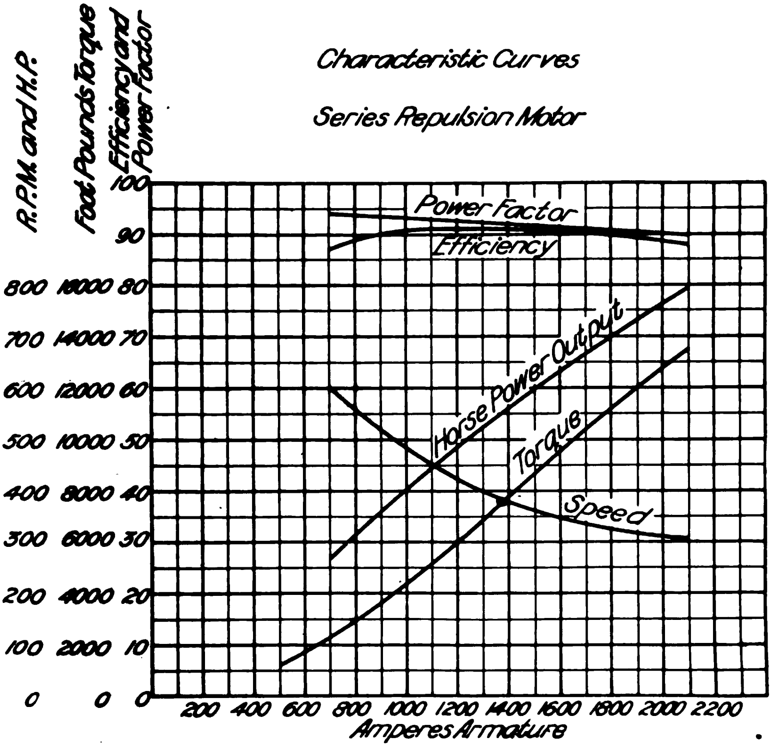

FIG. 1

Actual tests that have been made will best serve to show the starting ability of these motors. On one occasion a train of 250 tons was hauled by four motor equipments consisting of 125 h.p. motors. This train was started on a one per cent. grade, and as a further test two motors were cut out and the remaining two motors started this 250-ton train on the same grade.

DISCUSSION ON "THE NEW HAVEN SYSTEM OF SINGLE-PHASE DISTRIBUTION, WITH SPECIAL REFERENCE TO SECTIONALIZATION", AT NEW YORK, JANUARY 10, 1908.

(Subject to final revision for the Transactions.)

W. S. Murray: A retrospect always reveals more than a forecast. A perusal of the paper indicates to me, as doubtless to you all, that what has been touched upon is only a small percentage of the interesting and valuable data that could have been included were it at the election of the author to give his undivided attention to the subject.

I shall not attempt to apologize for what the paper lacks, and can simply say that odd moments, particularly those occurring while riding on the trains of the railroad company, supplied the time during which the article was written.

There has been no attempt to go into either the electrical or mechanical specifications of the distribution system. These were all included in the several contracts existing between the railroad company and the manufacturers and contractors, the general outline of which covers all points bearing upon the physical performance of the material furnished. As far as it was possible to anticipate, various weather conditions were considered in the design of all parts subject to changes of temperature, wind, and ice formation. We have passed through several snow, ice, and wind storms and combinations of these, and all the iron structures, messenger, trolley and feeder wires, have satisfactorily demonstrated the factors of safety which were included in their design.

A description of the electrical and mechanical details of the distributing system of the New Haven road has appeared in the columns of the engineering papers. My aim to-night has been more to acquaint you with some of our experiences rather than our theories. Therefore, fully conscious of many glittering omissions germane to the subject, and counting on the discussion to bring them out, I shall read the paper. [Here Mr. Murray read his paper.]

The discussion of double or single catenary construction on main-line electrification was intentionally omitted from the paper. A choice of the one or the other must be a compromise of a great many considerations, the principal ones being the number of tracks to be electrified, and local conditions; but there is one fact that has been conclusively demonstrated to me, namely, either the trolley wire or the trolley shoe must be flexible, whether the construction be for main or for branch lines. Of course in the single catenary construction a flexible contact conductor is provided. In the triangular construction, the contact conductor is rigid. This requires a flexible shoe, which in a degree is secured by the spring pantagraph arrangement. Experience, however, has forced upon me the conclusion that the pantagraph must be still further supplemented by a light but strong mechanism which will insure flexible contact between the shoe and trolley wire, thus not offering a great deal of inertia in movement when the shoe meets the hard spots of the line which exists at the catenary hanger points.

A form of construction we have adopted in our East Port Chester yard, in which the latitudinal catenaries are supported by cross-catenaries—in some cases spanning as many as ten tracks—has about it a great many attractive features, and I am not too sure but that experience will not bring out the possibility of using the cross-catenary for main line work. Such an arrangement, if more frequently reinforced with cross-bridge anchorages such as now used in the New Haven electrification, will bring a lighter and cheaper construction and possibly afford a greater opportunity in insulating the overhead system from ground. I can see no reason why single catenary spans need be made any less than those used in the double catenary construction, as the cross-rigidity that may be desired, can be obtained by tying into adjacent latitudinal catenaries, all of which, of course, are subject to the pull-off construction at present employed. Of course there are a great many pros and cons about this, and again we are forced to the conclusion that to-day is not the time for standardization, as it will pay not to accelerate our conclusions at a greater rate than the operating evidence upon which they should be based.

·Still another point that has not been touched upon in the paper, is the great flexibility offered in the double-switch arrangement of supplying power to a trolley wire at the two extremities of its section. It is readily seen that if trouble exists in one of the circuit-breakers supplying a trolley wire in any given section, this switch can be immediately cut out and all the power supplied from the remaining switch at the other end. This flexibility, of course, is secured in virtue of the low loss due to high-tension transmission, and the employment of by-passes or feeders, to which previous reference has been made.

An impression has come to me that I might have dwelt more fully on the details of the system of distribution. As stated previously, it has been so universally described in the engineering papers that I have rather felt I was writing about results and experiences with something, the general parts of which we were all acquainted. If I have universal support in this impression, I can only offer in amelioration, Diagram (4), which assembles all the links of our transmission chain, the functions of any one link of which is common knowledge.

L. B. Stillwell: I have not found time to read Mr. Murray's paper carefully and do not propose to criticize the sectionalization of the New Haven and Hartford trolley or its feeder layout. I have a very high opinion of the importance of these parts of the plant which unquestionably are too often neglected. There are cases where very large investments have been made to insure continuity of service in which, judging by results, the investment has not been made in the right place. Instances might be mentioned, in which, at great expense, excess generating capacity has been installed adequate to take care of the service, even in case of destruction of 50 per cent. of the total generating plant, and yet when the feeder layout was under consideration oversights apparently have occurred as the result of which very severe interruptions of service have followed. Unquestionably, therefore, criticism of the organization of supply circuits for large distributing plants, particularly for railway service, is highly beneficial. I say particularly in railway service, because in industrial power service the interruption of a feeder now ordinarily involves only a local and a very temporary failure of service; whereas in railway operation if we stop trains on one part of the line we are liable to hold up the entire operation of the railway.

W. B. Potter: The ordinary 600-volt trolley line is of little value as a standard with which to compare the 11,000-volt catenary under steam railroad conditions. Considered as an example of good construction, I have never seen the equal of the catenary to which Mr. Murray refers. As to the relative reliability and maintenance of such an overhead high-voltage trolley compared with a 600-volt third-rail, under conditions necessitating joint operation with steam, I believe this to be a debatable question.

I agree with Mr. Murray as to the desirability of a through feeder in parallel with the different sections; I do not see the need, however, of two such feeders on the same phase as the trolley wires. For local power the combination of the single feeder with the trolley wires would seem sufficient reserve. If any accident involved all four of the trolley wires, it would probably include the feeder as well; in case it did not, a single feeder could supply power beyond the break.

As to the length of the main-line sections, I favor from three to five miles, rather than less; as this question affects the reliability of operation, it seems that a reduction in the number of switching appliances would be favorable. Five-mile sections have proved satisfactory in third-rail operation, and there appears to be no reason for shorter sections with the high-voltage trolley, unless it is the greater liability of the longer sections to break down. It seems desirable, however, that at track cross-overs there should be a short section controlling the main-line and cross-over tracks, the better to insure cross-over movements in the event of interruption on the main-line sections.

Twenty-two feet seems to be a generally recognized standard height of trolley wire. It is unfortunate that this height cannot be maintained throughout, as it would then be possible to use a much lighter form of pantagraph. Overhead bridges, with their limited clearances, often necessitate a vertical movement of the collector of from seven to eight feet, and this condition requires a pantagraph structure more liable to derangement.

Depreciation of the catenary insulation from steam-locomotive smoke would naturally be expected, and the extent of trouble from this cause seems to have a bearing on the permissible trolley voltage. Conditions might well arise where either copper or efficiency would have to be sacrificed for reliability.

The suggestions with regard to time-relays and switch indication are in line with well established practice. As to the method of operating the circuit-breakers, I understand that they are at present controlled from the main power circuit. Should not some means be provided for operating these switches in the event of failure of power. As these circuit-breakers are near signal towers, where manual operation could be conveniently applied, would not this be the more reliable method. Lever connections would provide certainty of operation and would not interfere with the automatic tripping. The proposed change from the bridges to switch houses would simplify the mechanical connections.

There is no doubt as to the desirability of guarding against the spanning of two trolley sections, as there is always the possibility of one section being grounded. Such accidents will occur. If the two pantagraphs or trolleys are far enough apart to span the section insulators, the only safeguard seems to be a fuse located between the two collectors.

O. S. Lyford, Jr.: Mr Murray's paper is written from the point of view of operation of a multiple-track road. When viewed from the standpoint of single-track operation, this subject has some rather different aspects. For instance, Mr. Murray says:

> 1. In one-, two-, three-, or four-track railroads, the single-phase distribution should include, besides the trolley wires, by-passes or feeders.

I do not take exception to this statement as relating to two-, three-, or four-track roads, but it does not necessarily apply to single-track roads. The objects of sectionalization are three: first, to minimize the interference with the operation of the road in case of line trouble; secondly, to locate the fault quickly; and thirdly, to reach the fault with a work train.

As to the first object, to minimize the interference with operation I think it is quite apparent that a parallel feeder is not of much use as a by-pass in a single-track road of moderate length. Take, for illustration, the Erie road south from Rochester, Fig. 1. This is a single-track road, running from Rochester to Mount Morris. Power from Niagara Falls is received at a sub-station at Avon. At present the lines north and south from Avon are operated as two legs of a three-phase system, the common point being connected to the track. Avon is a junction-point with an east and west line of the same road. Rochester is about nineteen miles from Avon, and Avon is about fifteen miles from Mt. Morris. With a schedule speed of about twenty-four miles an hour and hourly service in each direction, it is apparent that a dead point anywhere on the line will, in a few minutes, block all trains on one side of the junction. The ability to move trains up to the dead point will not materially help the service.

The Erie line is divided into sections, but the principal object of sectionalization is to locate the fault quickly. The section breakers are " jumpered " through hand-operated switches and are placed near passenger stations or signal towers. If there is trouble, the system operator, by telephone orders, can have the section switches opened in sequence and quickly locate the section on which the trouble occurs. Mr. Murray speaks of special apparatus being developed to test for and locate faults quickly; if such apparatus be produced, it will probably be more convenient than the use of section switches.

Considering the third object—to reach the fault with a work train—even with short sections such as have been discussed tonight, the work train if operated by trolley could not get within three-quarters of a mile or so of the fault, and it would be impracticable for the men to have to go the rest of the way on foot to make the repairs. The logical conclusion, therefore, is that the work train should be operated by an independent unit, either a steam locomotive or a gasolene car, preferably the latter, because it is more easily put into service.

Independent operation of long sections, between important points, is desirable. Usually, however, this will be best accomplished by high-tension feeders, rather than by by-pass feeders operated at the trolley voltage. The Erie system has been planned so that if the electrification is extended beyond the limit for economical transmission at 11,000 volts (for instance from Mt. Morris to Dansville) the present transformers may be connected so as to obtain either 11,000 or 22,000 volts, and 22,000-volt feeders may be carried to the distant section, serving the trolley wire through auto-transformers. This plan allows transmission at double voltage and saves copper without appreciable complication.

Another case may serve to illustrate the conditions which arise in single-phase operation. The Denver & Interurban Railroad line from Denver to Boulder has a single-track main line and two single-track branches (see Fig. 2.) The power house is about two miles from the Louisville branch and 5.2 miles from the junction point. Power is supplied over two feeders from 11,000-volt, single-phase generators to the junction point. The length of the Marshall branch is 12.8 miles, Louisville branch 12 miles, and the Denver line 15.2 miles.

In this case it is obvious that there will be material advantage gained by being able to operate each branch independently, and provision has been made accordingly, but by-pass feeders for each branch would not help matters much in case of line trouble. The trolley wire, in this case, as with the Erie, has been provided with section breakers placed about four miles apart for convenience in locating faults.

There are other things to be taken into account besides the actual line trouble; that is to say, the problem is not merely to locate and repair the fault. On any railroad provided with

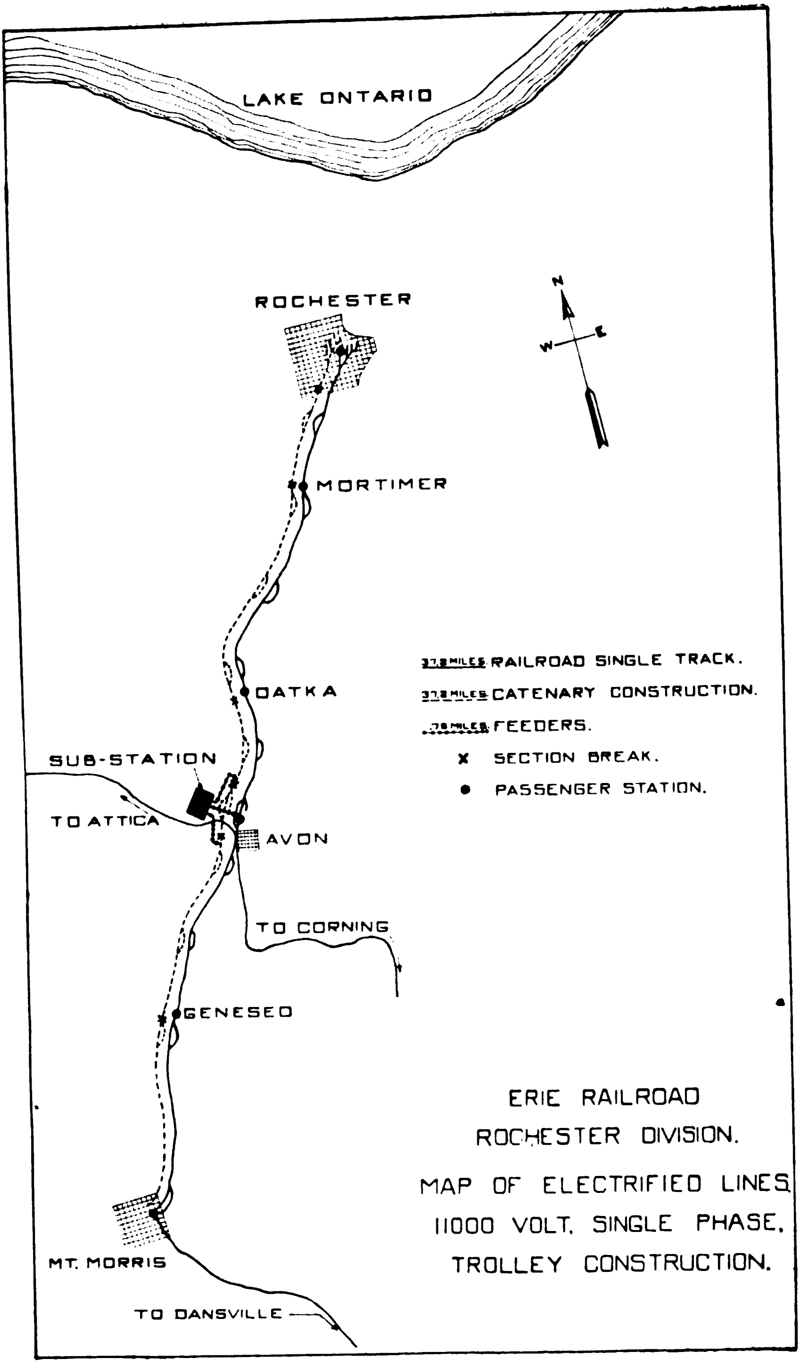
LAKE ONTARIO
ROCHESTER
N
W
E
MORTIMER
OATKA
SUB-STATION
TO ATTICA
AVON
TO CORNING
GENESEO
MT. MORRIS
TO DANSVILLE
37.8 MILES RAILROAD SINGLE TRACK.
37.8 MILES CATENARY CONSTRUCTION.
.78 MILES FEEDERS.
X SECTION BREAK.
● PASSENGER STATION.
ERIE RAILROAD
ROCHESTER DIVISION.
MAP OF ELECTRIFIED LINES
11000 VOLT, SINGLE PHASE,
TROLLEY CONSTRUCTION.

FIG. 1

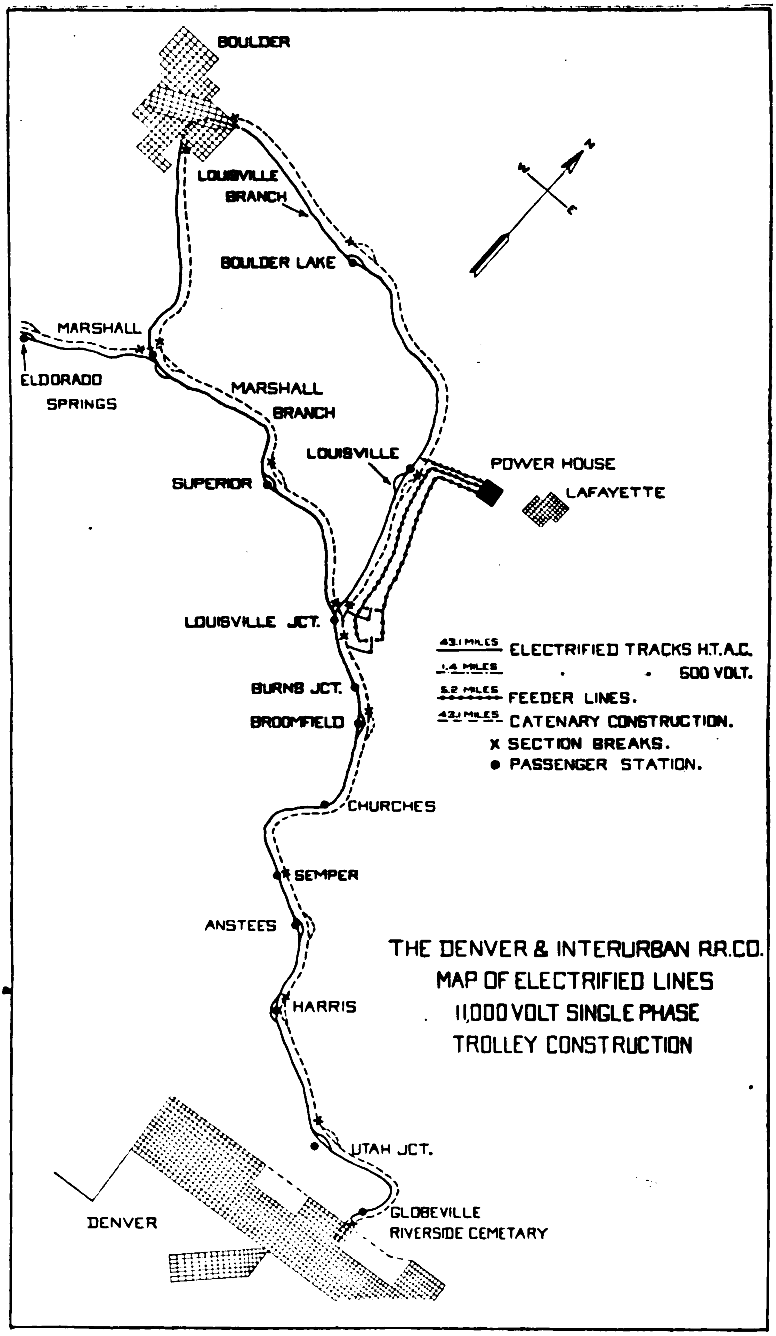
BOULDER
LOUISVILLE BRANCH
BOULDER LAKE
MARSHALL
ELDORADO SPRINGS
MARSHALL BRANCH
SUPERIOR
LOUISVILLE
POWER HOUSE
LAFAYETTE
LOUISVILLE JCT.
BURNS JCT.
BROOMFIELD
CHURCHES
SEMPER
ANSTEES
HARRIS
UTAH JCT.
GLOBEVILLE
RIVERSIDE CEMETARY
DENVER
43.1 MILES ELECTRIFIED TRACKS H.T.A.C.
1.4 MILES " " 600 VOLT.
5.2 MILES FEEDER LINES.
43.1 MILES CATENARY CONSTRUCTION.
X SECTION BREAKS.
● PASSENGER STATION.
THE DENVER & INTERURBAN RR.CO.
MAP OF ELECTRIFIED LINES
11,000 VOLT SINGLE PHASE
TROLLEY CONSTRUCTION

FIG. 2

a positive block system, the process of having the rules set aside so that a "special" can proceed against the block is about as difficult as to repair the fault itself. Most of the time of a service interruption is consumed in reaching the fault, not in locating or repairing it. Sectionalization does not help this part of the problem.

The natural answer to all of this is that the high-voltage trolley system must be put up so that line troubles rarely occur. That looks like quite a task with 11,000-volt operation, but as one gets acquainted with this high voltage construction most of the difficulties disappear. One important feature, according to present practice, is the exclusive use of porcelain for insulation. At first it looked as if the porcelain could not safely be subjected to the heavy physical strains of the catenary construction, but it has been found that standard forms of insulators, when properly harnessed, can be tested out with 14,000 lb. compression, and 22,000 volts electrical strain, at the same time. Thus far the physical strains in the catenary circuits do not exceed 5,000 lb. per wire, and there will be a factor of safety of about three for an insulator in a single wire or half that, if one insulator is used for both messenger and trolley wires. The use of built-up insulators is not promising; the use of wood, although the wood may be a good insulator, has the objection that if there is leakage across the wood and the wood is burned in two, then down comes the catenary construction. With porcelain properly harnessed, the only result of a broken insulator is reduced insulation. The line does not come down, because the harness is interlocked. With two insulators in tandem, the line will remain operative.

Mr. Murray's third recommendation of 22 ft. for general working distance of the trolley from the rail, seems to be about right, as has been said once or twice this evening, and this means a standard clearance of 24 ft. above the rail for the "through" and "under" bridges, and still greater clearances for other overhead structures, whenever physical conditions permit. In a large majority of cases (barring tunnels and city street-crossings) new construction can be designed for 24 ft. clearance without much difficulty or material effect in cost. The troubles of the electrical engineer will be materially reduced if the railways will make this the standard clearance for new construction.

The feature of high insulation factors for construction under low bridges should be characteristic throughout the entire installation, for the reasons which I have given. There is no reason for not having such an insulation factor.

Mr. Murray also speaks of the auxiliary wires passing under bridges, and advises the use of lead-covered cables with end-bells. A short section of insulated cable, in a grounded sheath, in the middle of a long overhead line, is a mighty difficult thing to install properly so that the insulation will not be frequently broken down. Inasmuch as the trolley wire has to go under the bridge, and the trolley must be bare, it would seem possible to put the auxiliary wire under the bridge in much the same way, and with equal safety.

One gratifying feature about catenary construction erected on grounded brackets or grounded bridges is that there are grounded structures close to and frequently above the live wires and consequently little probability of disturbance from lightning. The Rochester division of the Erie road, has been in operation for about eight months, and through nearly all the lightning season of last year there was practically no disturbance on the 11,000-volt system due to lightning, although there were bad thunder storms through that district, and a nearby high-tension line was struck repeatedly. On the other hand, in the single-phase system there occur occasionally heavy disturbances resulting in surges approximating lightning in severity, and if anything but porcelain be used for insulation (for instance, in the case of lead-covered cables above referred to) I should anticipate that such surges would occasionally break through the insulation.

On this Rochester division there is a telephone system on the same poles with the trolley line. With proper transpositions and suitable means for removing the " static " from the telephone line, it operates satisfactorily and without shock to the operators.

W. S. Murray: I am happy to feel that Mr. Stillwell bears me out along the ideas of a practical investigation. I think that mental reservations on this floor, where our mistakes may be brought out and discussed, is a great error. Our mistakes teach us more than our theories, and I think this floor is the place to discuss our troubles as well as our successes.

Mr. Potter spoke of pinning his faith to the third-rail instead of the overhead construction. In regard to that, I can simply say this is a problem much larger than the one we are discussing to-night, but I have reason to believe that on long-distance traction work the question of operating expense will unquestionably be the paramount feature, and hold the overhead construction and alternating-current transmission direct to motors a necessity. I can almost say that experience bears me out in this regard, even within restricted zones of electric traction.

I think that the necessity of two feeders can be explained quickly by saying that in the event of trouble, the interlocking of the feeder system as established on the New Haven road is such that if trouble occurs on one feeder, by by-passing around through switches on the anchor bridges we are enabled to cut out any feeder-section and make repairs, thereby giving a more reliable continuity of service.

I thoroughly agree with Mr. Potter that the sections should be greater in length. I think three to five miles sounds reasonable, but local conditions govern better what the actual distance should be. I am quite convinced that were we to draw up specifications for the New Haven electrification again, I would be in favor of a longer section. This, as brought out in the paper, does not interfere with the coterminous arrangement of towers, which is most important.

In regard to pantagraphs operating under low bridges, Mr. Potter has brought out an important and deleterious feature of the overhead system. It is a problem that must be solved. We first started our electrification by a system of supports under low bridges, at very short intervals, and the result was, due to the effect of the locomotive blasts, that grounds developed very rapidly. This trouble has been overcome by eliminating the large number of supports, resorting to only two; and, instead of having the insulation in the middle point directly over the track, as at first installed, it has been placed at the side, so that the locomotive blasts do not affect the main insulators. Since we changed the construction to the latter arrangement, we have experienced absolutely no trouble in the grounding of the contact conductor (or messenger cables which are connected to it) under low bridges. This form of construction has been in use for four or five months.

In regard to the fact that for mechanical reasons we have to increase the copper in overhead construction, high tension work, the fact also must not be overlooked that the total copper is still in a minute ratio to the amount of copper required for an equivalent amount of power with the same loss transmitted on the alternating-current direct-current system.

Operating the anchor bridge switches by levers would bring an increase of operating cost. I do not approve of this particularly as lever arrangements in switches have been abandoned as cumbersome in places where quick action is required, and such a place as the operating towers calls for quick action.

In general, I agree with Mr. Lyford about the single-track feeder arrangement. In its application to long distances, however, I think a feeder arrangement for single track construction is quite necessary, particularly where the headway is short and the traffic heavy. Should such trouble as he spoke of develop in the middle of the line, it is not uncommon in railway practice to operate to that point on both sides. In such a contingency, the feeder or by-pass offers quick relief, is not costly, and is constantly saving power. I certainly agree with him in regard to porcelain insulation in the place of moulded material, if it is possible to obtain the tension and compression strains in porcelain that is obtained in using molded material.

Mr. Lyford's suggestion to use the same form of feeder construction under low bridges as is adopted in the trolley is a good one, provided the clearances can be obtained under the low bridges in question. Abutment walls are so near to the tracks that it becomes a rather difficult thing to put in this kind of construction, especially if, besides feeders, other wires, such as power wires and signal wires have to be taken care of.

DISCUSSION ON "THE NON-SYNCHRONOUS GENERATOR IN CENTRAL STATION AND OTHER WORK". "SOME DEVELOPMENTS IN SYNCHRONOUS CONVERTERS". "SOME FEATURES OF RAILWAY CONVERTER DESIGN AND OPERATION", AT NEW YORK, FEBRUARY 14, 1908.

(*Subject to final revision for the Transactions.*)

C. F. Scott: The three papers presented to-night deal with alternating-current apparatus and show the wide variations in methods which are practicable with alternating current but not with direct current.

When a new machine or method is proposed, it frequently happens that it may accomplish the specific purpose for which it is intended, but it may involve some incidental feature that renders the whole inoperative or inadmissible. Mr. Waters not only describes the generator itself but points out the various advantages over synchronous generators in its construction and also its marked advantages in operation. Instead of introducing objectionable characteristics, it presents many points of advantage—reduced current on short-circuit, a smooth wave-form and damping action due to the short-circuited element, which exerts a steadying and soothing effect throughout the whole system, that tends in turn to prevent hunting and surges.

The paper indicates that there should be a considerable commercial field in which this type of generator will have an important application.

Mr. Stone presents six methods of voltage regulation of synchronous converters. It may be noted that the alternating-current booster may be provided with either a shunt field winding or a series field winding, or both. If a series field winding carry the current from the synchronous converter, then the compounding may be effected automatically by a practically straight-line law over a considerable range.

A comparison of the relative characteristics of the several methods of voltage regulation is of interest. In several a mechanical adjustment of the apparatus is necessary. In the case of the transformer with loops, the connection must be shifted from one loop to another. In the induction regulator mechanical rotation must take place. The reactance involves no such adjustment. In the methods in which field current is adjusted, the windings may be either shunt windings for hand control or series windings for automatic control. Auxiliary automatic control apparatus can, of course, be applied for operating rheostats, regulators and the like. The power-factor, that is, the ratio between true and apparent watts, varies when reactance is used, or the methods in which the field poles are divided into parts which are unequally excited. The power-factor is practically unaffected when transformer loops, induction regulators, or boosters are employed. The wave-form is not affected except in those cases where the field poles are divided into two or more parts. The range of voltage variation is relatively small with reactance. It is probably small with the methods in which the field poles are divided into parts, unless considerable variations in power-factor or wave-form are admissible. The range may be very large when other methods are employed. These characteristics are brought together in the following table:

Method	Inherently automatic	Hand adjustment	Power-factor	Wave-form	Range
1. Transformer loops	—	Yes	O.K.	O.K.	Large
2. Reactance	Yes	Yes	Variable	O.K.	Small
3. Induction Regulator	—	Yes	O.K.	O.K.	Large
4. Booster	Yes	Yes	O.K.	O.K.	Large
5. Woodbridge	Yes	Yes	Variable	Variable	Small?
6. Burnham	Yes	Yes	Variable	Variable	Small?

Paul M. Lincoln: The scheme proposed by Mr. Woodbridge for changing the direct voltage of a synchronous converter, as well as the modification proposed by Mr. Burnham, is ingenious, but I believe that Mr. Stone's descriptions are altogether too brief to be satisfying to the engineer who contemplates making use of them. At the time Mr. Woodbridge's device was originally proposed, considerably over a year ago, I became familiar with an analysis of the scheme; this analysis seemed to show that the objections to the use of such a scheme outweigh the advantages. A repetition of this analysis within the last month leads to the same conclusion. Some of the steps in this analysis may be of sufficient interest to reproduce in this discussion.

Wave-form. The first question that arises when contemplating the use of this split-pole converter is its effect upon wave-form. These questions might naturally be put as follows: will the wave form of the split-pole converter depart materially from a sine wave? If so, how much will be the departure? Will such deformation, if it occurs, have any bad effect upon the converter itself or upon any part of the system to which the converter is connected?

The first two questions are probably best answered by a number of series of curves which were prepared in the course of the above mentioned analysis. It is well known that with a given field-form, the distributed winding of a converter gives rise to an electromotive force wave-form which is subject to quite exact determination. The division of the converter field into sections, and the provision of means to excite these sections independently of each other, gives control over the field form and therefore over the alternating-to-direct voltage ratio. As the field form changes, however, the electromotive force wave-form of the converter also changes. To what extent this takes place for certain assumed field forms is indicated in Figs. 1 to 7. Figs. 1, 2, and 3 show what may be expected of a converter with its pole divided into three sections, and Fig. 4, 5, 6, and 7 what may be expected with a pole of two parts.

Fig. 1 shows, first, six possible field forms; secondly, the electromotive force wave-forms that these field forms give rise to; and thirdly, the sine wave equivalent to the determined wave-form. The wave-forms in this series, as well as all the others, are those across an electrical diameter, in other words, they are the wave-forms that would be taken across opposite rings of a six-phase or a two-phase converter. With a field form other than a sine, the wave-form across an electrical diameter deviates from sine form less than that across any chord. It gives, therefore, the most favorable condition so far as deviation from sine form is concerned. The narrower the band of conductors the more closely will the electromotive force wave-form approach the field form. A single conductor, for instance, will give rise to an electromotive force wave-form exactly similar to the field form.

The figures at the right indicate, first, the per cent. variation in direct voltage over that which would be obtained with an electromotive force wave of sine form; secondly, the deviation in the resultant electromotive force wave from its equivalent sine wave. The sine deviations are calculated according to Institute rules.

Fig. 1 assumes a three-part pole with all three parts equal, and shows the variations through which the converter field must be carried to vary the direct voltage from +13 per cent. in the lowermost figure to —15.3 per cent. in the uppermost. The first condition entails a deviation from the equivalent sine of 74 per cent. and the second of over 23 per cent. The direct-current variation can be carried still further by further deforming the field, but at the limits given in this series the field strength at maximum direct-current variation is more than double that at minimum direct-current variation. Probably no converter designer would wish to consider a further field deformation.

Fig. 2 shows what may be expected if the outside sections of the field pole are reduced from about 33 per cent. to about to 20 per cent. each of the total pole area. The direct-current variation in this series is carried from 12.8 per cent. + to 50.8 per cent. The first condition entails a sine deviation of about 32 per cent. and the last 50 per cent. Here again the field deformation and relative field strength are carried to an extreme at the limiting conditions.

Fig. 3 shows what may be expected if the middle section of the pole is made considerably narrower than the outside sections, a condition the reverse of that in Fig. 2. In this third series the middle section is about 20 per cent. the total pole width. The limiting direct voltage values in this series are 8.2 per cent. plus, entailing 39 per cent. sine deviation, to 6.5 per cent. minus, entailing 12 per cent. sine deviation.

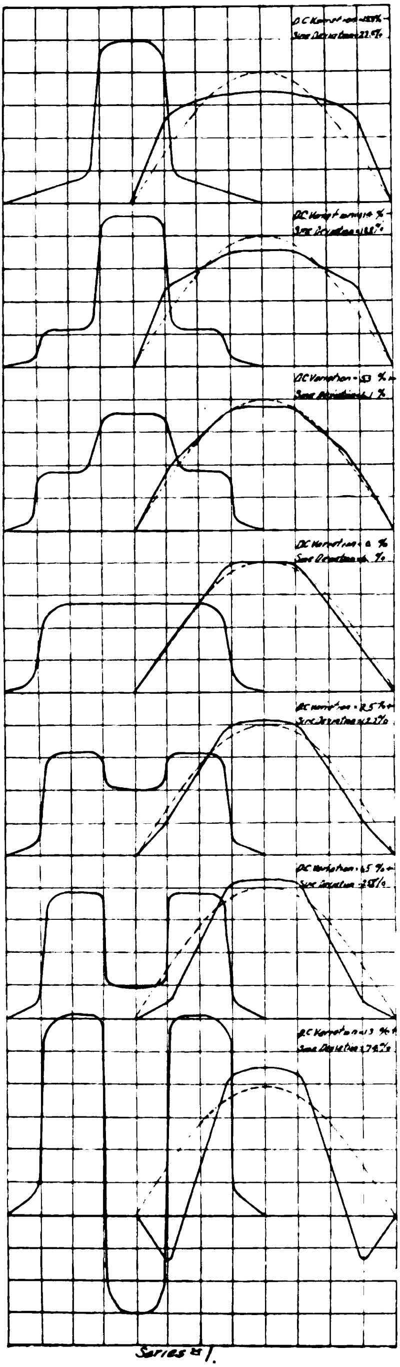
D.C. Variation = 53 %
D.C. Variation = 0 %
Series #1.

FIG. 1

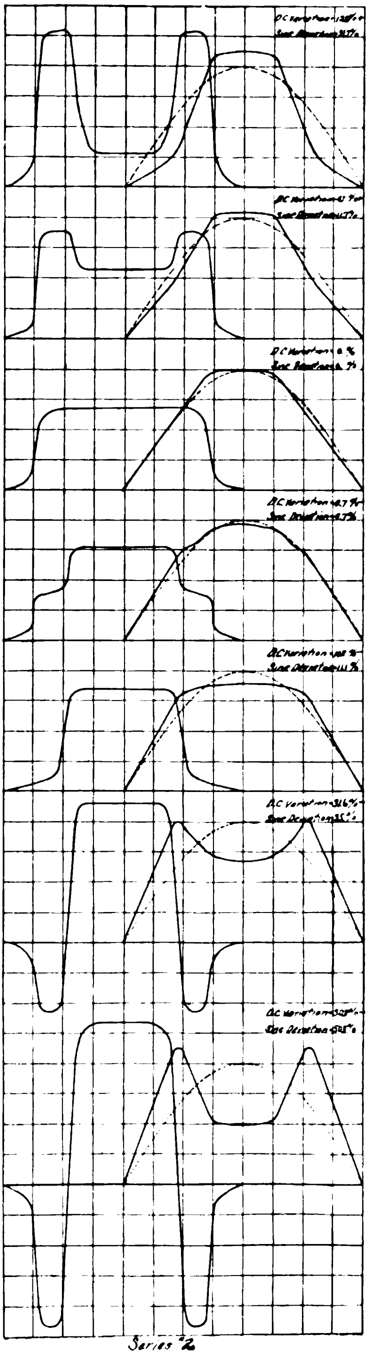
D.C. Variation = 0 %
Series #2

FIG. 2

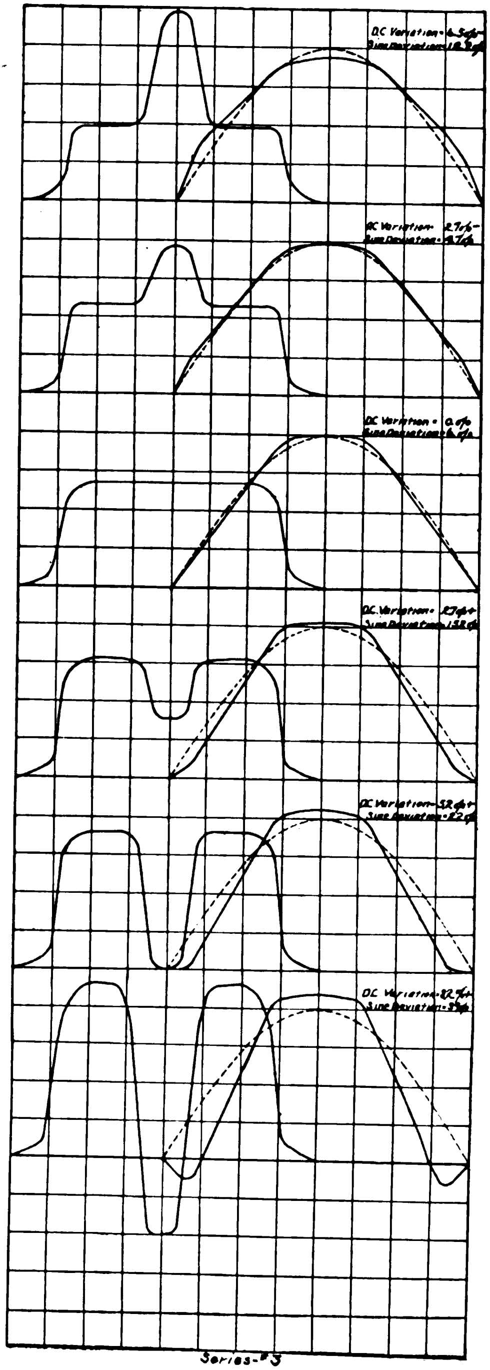
DC Variation = 6.5%−
Sine Deviation = 12.3%
DC Variation = 2.7%−
Sine Deviation = 4.7%
DC Variation = 0.0%
Sine Deviation = 6.0%
DC Variation = 27%+
Sine Deviation = 15.2%
DC Variation = 52%+
Sine Deviation = 22%
DC Variation = 82%+
Sine Deviation = 35%
Series-#3

Fig. 3

Considering the three-part pole proposition as a whole, we find that to obtain a given direct voltage variation there is entailed a deviation from the equivalent sine wave of at least as great a per cent. as the direct-current variation, and for most conditions a deviation of two or three times as great.

Fig. 4 shows what may be expected with a two-part pole, the two parts being of equal area. In this series the direct-current variation is carried from 0.2 per cent. plus, to 68 per cent. minus, the former condition having a wave-form fairly close to a sine while the latter deviates over 30%. It will be seen in this series as well as in all others dealing with two part poles that a good wave-form is obtained only at the upper range of direct voltage. The mid-voltage position has a sine deviation of at least 25 per cent. and the minimum voltage is not much worse. This is a characteristic difference between the three-part pole and the two-part pole. In the three-part arrangement the mid-voltage position can be made to have a wave fairly close to a sine form, while in the two-part pole arrangement the mid-voltage position has a deviation much greater than half that for minimum voltage. However, this is about the only advantage the three-part pole has over the two-part pole.

It will readily be seen from an inspection of curves in No. 4, that the minimum direct voltages are obtained by an arrangement of field which corresponds closely to shifting the brushes of an ordinary converter forward or backward until the direct voltage between them is reduced the required amount. Instead of moving the brushes, the same effect is obtained by reversing a part of the field. In this series the direct voltage might very easily be carried down to zero with not very much additional deviation from sine wave.

Fig. 5 shows a series with the pole face divided in 70 per cent. and 30 per cent. sections instead of equal sections. The field deformation in this series is carried to such a point as to give a direct voltage variation of about 20 per cent, each way from the mid position. The maximum deviation from sine form occurs, as pointed out above, at the minimum direct current position and is about 25 per cent. The mid direct-current position entails a sine deviation of between 15 per cent. and 20 per cent.

Fig. 6 is worked out for a condition of approximately 15 per cent. direct voltage variation each way. The maximum sine deviation is 20 per cent., and at the mid-voltage position a little less than 15 per cent. The small section of field is about 20 per cent. of the total in this case.

Fig. 7 is worked out for a direct-current variation of about 10 per cent. each way and shows a maximum sine deviation of 15 per cent. and a little less than 10 per cent. at mid direct voltage. The small pole horn is about 15 per cent. of the total pole in this case.

It is probable that the proper shaping of pole pieces may be made to give deviations from sine form somewhat less than I have worked out in this series of curves, but the very nature of the case will prevent results that are materially better. They may be worse.

It is patent from the foregoing that the user of a split-pole converter can expect very considerable departures of the converter wave from the generator wave. The percentage deviation from sine form will be considerably greater than the percentage variation in direct voltage each way from mid direct-current position when considering a two-part-pole converter. For reasons that will appear later, this form is the only feasible one. The next question is: will this deviation from sine wave have any bad effect on the converter or on the system to which it is connected?

When the wave-form of a synchronous machine is at variance with that of the system upon which it is operating, currents will flow, due to these differences in electromotive force wave. Ordinarily there are two actions taking place to limit these circulating currents; first, the impedance of the circuit through which they flow; secondly, and by far the more important, the fact that these circulating currents tend to modify the electromotive force waves of both the generating system and the receiving apparatus. If any specific piece of receiving apparatus be of relatively small capacity, as is usual, the greater part of the modification takes place in that receiving machine. In the case of split-pole converters, this field modification due to the circulating-current action is entirely absent. In order to obtain the desired direct voltage variation, the deformation of field and consequently of wave-form must be carried to the required point. The efforts of the circulating currents to bring back the field form to normal, must be neutralized and overcome by the exciting force tending to deform the field. The only impediment in the way of these circulating currents, therefore, is simply the impedance of the circuit. On a very large system the impedance outside the converter becomes reduced very close to zero and practically the only impedance offered is, therefore, that of the converter armature itself.

Commercial considerations usually call for a direct-current variation of 10 to 15 per cent. each way from normal. The analysis already given shows that with such a direct-current range a third harmonic under maximum deviation conditions of 15 per cent. is quite possible. Mr. J. E. Woodbridge has assigned 5 per cent as the value of the reactance of the armature of a converter. For third-harmonic frequency this value will become 15 per cent. Assuming such a converter to be directly connected to a very large alternating-current system, a triple-harmonic current will result, of a volume equal to the full-load current of the converter. Still higher harmonic currents will flow, and the maximum deviation of the current wave will be still greater than that represented by the full-load third harmonic.

While not at all outside the range of possibility, the above conditions will be unusual because on a very large system, the

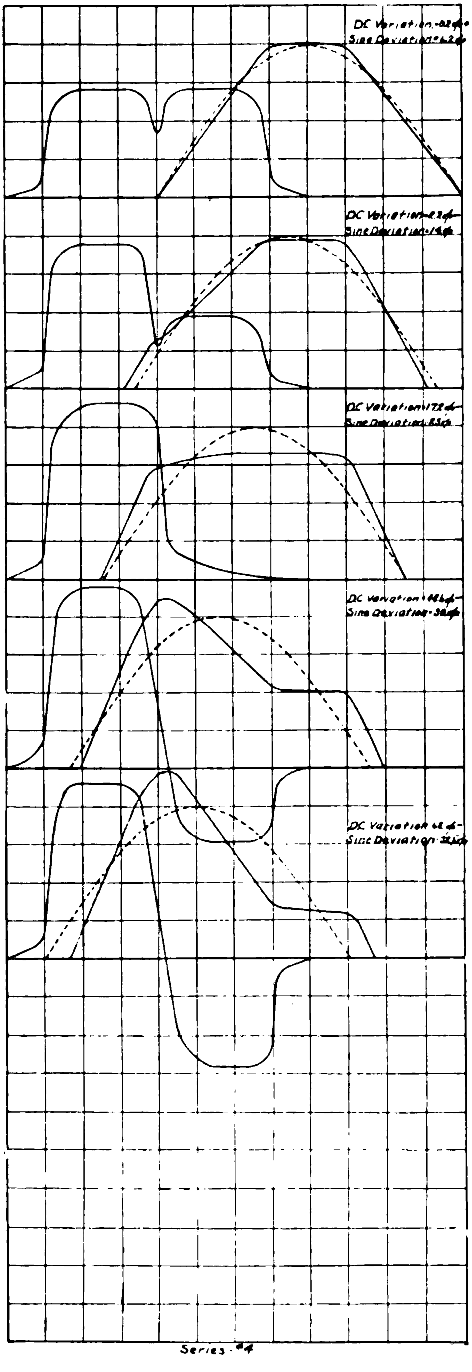
DC Variation -0.2%
Sine Deviation 6.2%
DC Variation 2.2%
Sine Deviation 1.5%
DC Variation 17.2%
Sine Deviation 8.5%
DC Variation
Sine Deviation
DC Variation
Sine Deviation
Series #4

Fig. 4

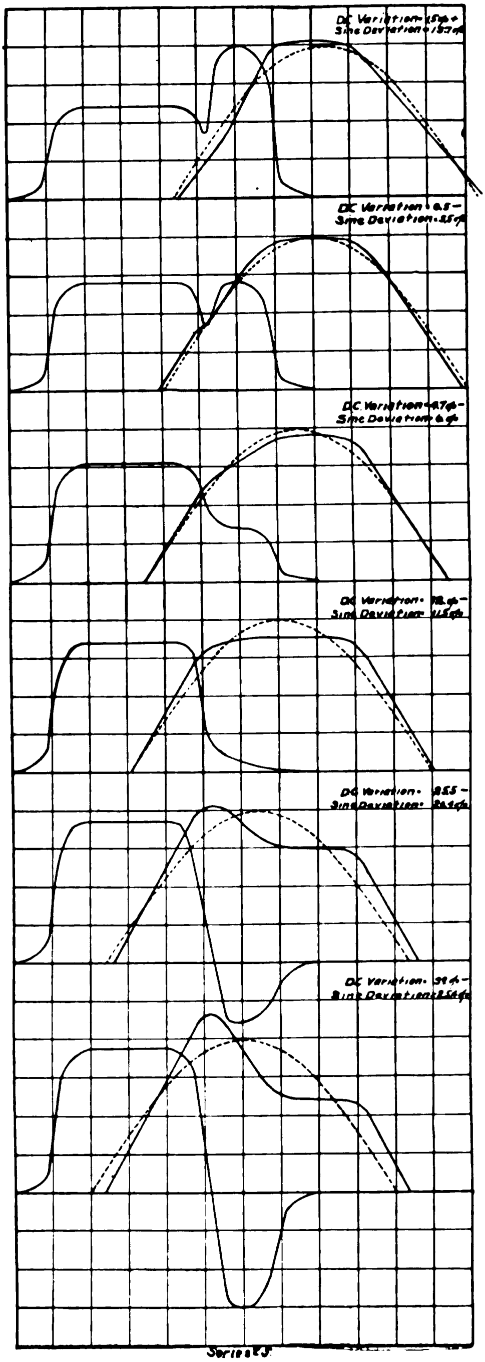
DC Variation = 15% +
Sine Deviation = 15.7%
DC Variation = 6.5 −
Sine Deviation = 3.5%
DC Variation = 4.7% −
Sine Deviation = 6%
DC Variation = 18.% −
Sine Deviation = 11.5%
DC Variation = 25.5 −
Sine Deviation = 26.1%
DC Variation = 39% −
Sine Deviation = 25.4%
Series E.S.

FIG 5

converter will undoubtedly have transformers in series with it. The reactance of these transformers will assist in keeping back the circulating currents of higher harmonics. However, considering that the third-harmonic current reduces to a possible 50 per cent., it still remains a volume too large for the operating engineer to tolerate.

The above figures apply only to the behavior of one of these converters when connected to a relatively large system, where the electromotive force wave-form of the system is not perceptibly affected by the circulating currents of higher frequencies. Where the system wave-form is so affected, the circulating currents will be reduced in proportion to the modification of the generated wave-form. At the same time, however, other difficulties will be introduced, because in this latter case the wave-form of the system is largely at the mercy of the operator in charge of the split-pole converters in question. Assume a case, for instance, where one-half the load of a generating system consists of a bank of these split-pole converters, and the other half a bank of ordinary converters. The adjustments of direct voltage on the split-pole converters will, as indicated in the foregoing analysis, change the wave-form of the system. This, in turn, will cause circulating currents in the ordinary converters that will change their wave-form and, as a result, their alternating-current—direct-current ratio. We find, consequently, that the alternating-current-direct-current ratio not only of the split-pole converters on such a system is subject to modification, but also all the other converters as well. Usually such a condition of affairs would be found to be intolerable.

Power-factor. Mr. Stone says that the power-factor of these split-pole converters can be held at unity throughout the entire range of direct voltage. Before we can accept Mr. Stone's statement, a further explanation of exactly what he means is necessary. If Mr. Stone intends to convey the idea that the field of the converter can be so adujsted that the current of fundamental frequency is in phase with the electromotive force of fundamental frequency, the statement can be accepted. If, however, he means to convey the impression that the ratio of kilowatts input to kilovolt-ampere input can be held at unity, then the statement is debatable. A power-factor meter indicates the phase relation of the current of fundamental frequency to the voltage of fundamental frequency; if currents of higher frequencies and large volume are flowing, a power-factor of unity, as indicated by a power-factor meter, does not at all mean that the volt-amperes are equal to the watts. It seems probable that Mr. Stone is basing his statements upon observations of power-factor meters when used in connection with split-pole converters. The above analysis shows that it is impossible to keep the volt-amperes and the watts equal in any case where currents of more than one frequency are flowing. When a given alternating-current—direct current ratio is to be obtained, it is impossible to adjust the field strengths of one of these converters so as to eliminate these currents of higher frequencies. It is, therefore, manifestly impossible to adjust the fields so as to make unity power-factor throughout the entire range.

Capacities and costs. When considering the capacity that can be obtained from a given amount of material made up into one of these split-pole synchronous converters, we find that for equal outputs the amount of material for the split-pole is largely increased over what it would be ordinarily. Reference to the various series of curves that have been shown indicates that the field strengths in these converters at the maximum point vary all the way from 10 per cent. to 15 per cent. above that at the minimum point, to more than double that at the minimum point. Since the iron of the armature of the converter is capable of being worked only to a certain maximum magnetic density, it follows that the amount of iron in the armature must be increased with a split-pole converter in approximately the ratio of the minimum field to the maximum field. Reference to the series of curves shows that the ratios of minimum to maximum field in the three-part pole converters is very large, so large in fact that a converter built on this principle will require so much additional material a; to make it an uncommercial machine. The same criticism does not apply to the two-part pole; in that case the ratio of minimum field to maximum field is roughly the ratio of normal direct voltage to maximum or minimum; in other words, if 10 per cent. machine range is required, the amount of material in the armature need be increased approximately only 10 per cent. over what it would be with an ordinary converter. This comparison is pointed out in order to show that a commercial machine can be made only when the two-part pole converter is considered.

The original Woodbridge scheme of using three parts makes so great an increase in size and cost of the resulting machine as to put it practically out of the question.

Efficiency. Considering the relative efficiencies of the split-pole converter and the ordinary type, we find that the split-pole converter increases considerably every item of loss that enters into efficiency. The field loss evidently must be considerably increased because: first, there are two parts to every pole to be excited; secondly, because the exciting tendencies of the higher harmonic frequency currents must be overcome by exciting energy put into the fields.

The iron loss is also materially increased, particularly at the lower direct-current limits when considering the two-part-pole converter. Reference to the curves indicates that the frequency of reversals in magnetism are twice as great when obtaining a minimum direct voltage as they are with a converter of normal type. This means, naturally, an iron-loss increase in about the same proportion.

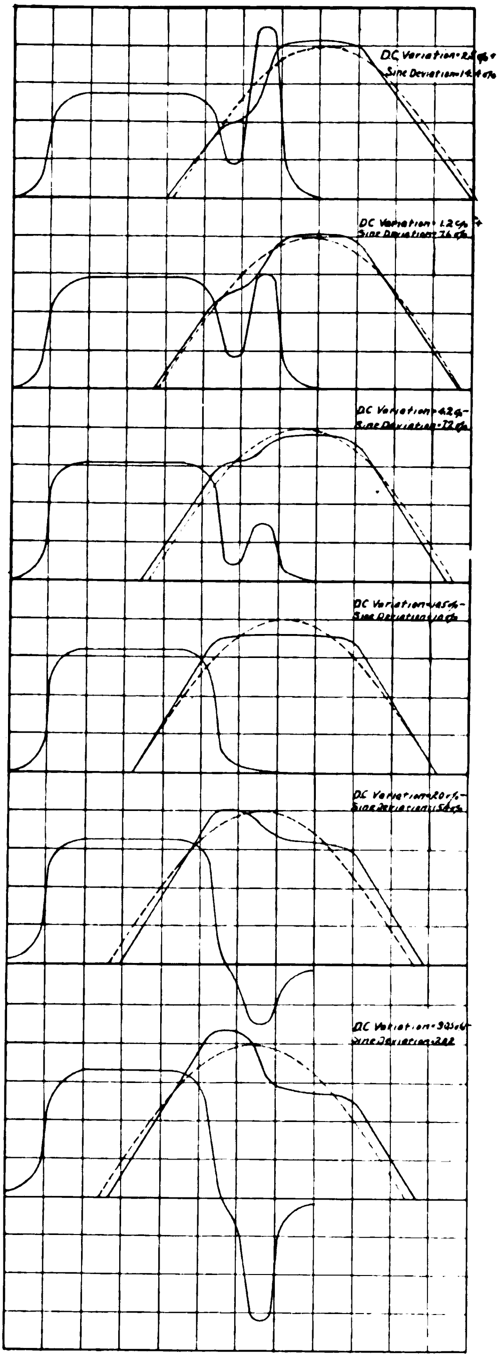
DC Variation=2.5%+
Sine Deviation=14.4%
DC Variation=1.2%+
Sine Deviation=7.6%
DC Variation=4.2%-
Sine Deviation=7.2%
DC Variation=14.5%-
Sine Deviation=10%
DC Variation=20%-
Sine Deviation=15.6%
DC Variation=32.5%-
Sine Deviation=22.2

FIG. 6

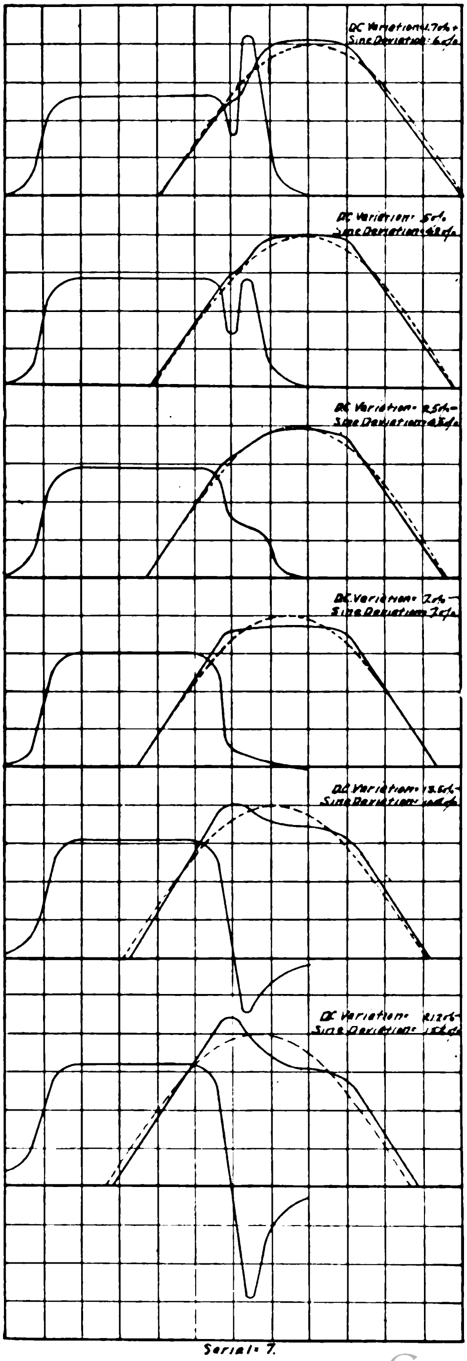
DC Variation 4.7% +
Sine Deviation: 6%
DC Variation = 5%
Sine Deviation = 4.8%
DC Variation = 2.5% –
Sine Deviation = 4.5%
DC Variation = 2% –
Sine Deviation = 7%
DC Variation = 13.6% –
Sine Deviation =
DC Variation = 21.2% –
Sine Deviation =
Serial = 7.

Fig. 7

On account of circulating currents of higher frequencies, the armature copper-loss is also increased above what it would be with a converter of normal type. The amount of increase of this armature copper-loss depends, as pointed out in previous paragraphs, upon the relative size of the converter, and the system to which it is connected, as well as upon the amount of deviation of converter wave from the generated wave. A number of calculations of actual cases have determined that the efficiency of these split-pole converters is as low as—in most cases lower than—the efficiency of the combined converter and separate booster which Mr. Stone describes in another paragraph.

Commutation. As mentioned in a previous paragraph, the operation of the two-part-pole converter at the lower range of direct voltages gives a result somewhat similar to shifting the brushes backward or forward into the active field. The main difference is that a notch of any desired width can be made in the pole opposite the point where the brush rests upon the commutator. When the smaller pole-horn is excited in the same direction as the main pole, the field at the point where the brush rests upon the commutator will be very close to zero. When, however, the small pole-horn is excited in a direction the reverse of the main pole-horn, the excitation of the small horn is then in the same direction as the pole just the other side of the adjacent direct current brush. Necessarily the field at the point where the brush rests upon the commutator will change materially, depending upon whether this small pole-horn is excited in the one direction or in the other. There is no question but that commutation can be properly carried out, even with this variation of field strength at the point where the brush rests upon the commutator. It will, however, require a machine which has considerably better inherent commutating characteristics than would be the case were a converter of the ordinary type used.

Resonance. In the ordinary system, circulating currents of the higher harmonics tend to efface themselves. With the split-pole converter, however, under minimum direct voltage conditions these higher harmonics are apt to be pushed to a point where the currents resulting from them become a very considerable portion of the total current flowing. A system which contains cables always has present the possibility of there being set up a condition in which resonance will take place. In the past, very little trouble has been experienced with resonance, for the reason, as stated above, that the higher harmonics rapidly tend to eliminate themselves. If, however, split-pole converters are used upon systems where underground cables are used to any great extent, I would not be at all surprised to find that the resonance will become of very considerable importance. In changing one of these split-pole converters from its minimum direct voltage to its maximum, harmonics of almost limitless frequencies will be set up, and their amplitudes will be constantly caused to decrease and diminish. If, therefore, there is any tendency for resonance to occur anywhere in the system, the presence of one of these converters would undoubtedly search it out and supply the proper frequency of electromotive force to make it become active. Systems, therefore, which have any great amount of underground cable should carefully investigate the possibility of such a condition arising, before deciding to adopt machines of this character.

The alternative which Mr. Stone describes; namely, a converter upon which a separate machine is mounted, having the same number of poles as the converter, has, in my opinion decided advantages over this split-pole converter, for the following reasons:

1. Its wave-form remains constant and fixed, since the added voltage is of fundamental frequency, whereas the split-pole converter is apt to set up harmonics of almost any possible frequency and of amplitudes which may easily circulate currents up to full-load values.

2. The power-factor of the booster converter can be held at unity throughout its entire range of direct voltage, whereas the split-pole converter cannot.

3. The efficiency of the booster converter is not less, but in most cases considerably more than the split-pole converter.

4. The commutating conditions of the booster converter remain fixed throughout its entire range of direct voltage, whereas in the split-pole converter, careful attention must be given to the point of commutation on account of the changeableness of the field at the point where the brush rests upon the commutator.

5. The cost of the split-pole converter are greater than an equivalent capacity of simple converter, and probably as great as the combined cost of simple converter and booster.

6. The booster converter introduces no higher harmonic voltages into the system and consequently danger of resonance is no greater than it has been in the past. The same cannot be said of the split-pole converter.

7. All parts entering into its construction are standard. It is simply an assembly of well-known and thoroughly tried out machines of standard design.

F. G. Clark: The paper presented by Mr. Waters advances the conclusion that certain advantages possessed by non-synchronous generators are sufficient to warrant their installation in new plants in place of synchronous generators; in present plants where new units are required; in 25-cycle gas-engine installations, and for use with synchronous converters in place of large slow-speed direct-current generators. This proposition is sufficiently radical to call for careful consideration by any one interested in power plant work.

Speaking from the standpoint of an operating engineer, I must confess to the belief that the author in his enthusiasm over advantages, some of which must be admitted as important, neglects to consider certain disadvantages which preclude the use of the non-synchronous generator in large power stations where synchronous generators are now installed. The advantages appear to be.

1. *Excellent mechanical construction.* This probably relates to the generator and as the stator differs but little, we must pass to the rotor which is described as advantage No. 2.

2. *Absence of direct-current rotating fields.* There can be no question but that this is a distinct advantage. The only reservation is the possibility of trouble due to a small air-gap on a large machine.

3. *Absence of direct-current excitation.* As we have already discussed the rotor, this can apply only to a comparison of the exciting apparatus required in each case. The claim that the excitation of a non-synchronous generator can be controlled from a distant sub-station does not appeal to me as practical. There are a few possible happenings between a sub-station and a power station which would cause either voltage-rises or interruptions chargeable to such operation. I believe it safe to say that the synchronous converter with its starting direct-current, engine-driven generator must be located at the power station.

4. *Facility for control of load by motor control of steam governor.* The synchronous generator can be similarly controlled and no advantage obtains.

5. *Unequal distribution of load between generators does not produce cross-current.* The unequal distribution of load between synchronous turbo-generators produces a flow of magnetizing current where there is a difference in excitation, and a division of current where there is a common neutral bus-bar. There is no hunting and no undue heating, therefore no practical advantage obtains.

6. *General simplicity and flexibility of operation.* The simplicity of the rotor has been acknowledged and cannot be included here. The field rheostat and the synchronizing arrangements of the synchronous generator are not required, but a reactive coil and a governor control are requisites. No practical advantage obtains.

7. *Requires less excitation than synchronous generators.* Under certain favorable conditions on a large system the total power for excitation will be considerably less for non-synchronous generators. When, however, the difference in economy due to the compensating requirements, and the operation of very large units on very light loads is taken account of, the advantage of the non-synchronous generator will not be great, or will disappear.

8. *High efficiency.* This is not an advantage unless it be relatively to a lower efficiency in other types of generators. The author admits that there must be high speed, low fre-

quency, and low voltage or the non-synchronous will not compare favorably with the synchronous generator. This limits the comparison and eliminates the advantage of efficiency except in certain particular cases.

9. *Beneficial characteristics relatively to resonance and short circuits.* It is claimed that the non-synchronous generator possesses the proper characteristics to prevent, or rather lacks those characteristics of the synchronous generator which promote, high-power surges, resonance, and other electrostatic phenomena. The author assumes that resonance and other electrostatic effects are produced either by short-circuits or faulty sine-waves, and that the non-synchronous generator avoids these effects by depriving short-circuits of their high power, and by giving forth only sine waves.

While admitting that these are decided advantages when compared with a majority of large installations, I do not believe that generators are ever the primary cause of electrostatic troubles outside of the station. Good line and cable construction, effective lightning protection, the grounded neutral, and automatic relays tend to lessen the primary causes and curtail the disastrous effects of insulation breakdowns. High-power short-circuits require a time-element to produce disastrous results. If the excitation of the alternator can be cut down proportionately to the speed with which the load approaches short-circuit conditions, and if also this action can be accelerated so that a short-circuit will develop in less than a second, we have accomplished just what Mr. Waters claims for the non-synchronous generator. This is accomplished at the Pennsylvania power station by using an induction motor generator for excitation, and a Tirrill regulator for holding up the voltage. The characteristics of a combination including an induction-motor-driven exciter with series and shunt field, the latter controlled by the main generator voltage, are suitable for maintaining operation under all conditions except those due to short-circuits. When a short-circuit occurs, the field of the exciter is " boosted " in an endeavor to hold up the generator voltage. This accelerates the approach to short-circuit conditions, and produces a practically instantaneous interruption, by automatically " killing " the excitation. This scheme was adopted upon the assumption that the interruptions in railway service were of less moment than the troubles consequent upon an endeavor to hold up the excitation at all hazards. In this particular case, therefore, the non-synchronous generator does not possess an advantage.

10. *Overload capacity.* The overload capacity of five times normal full load is an advantage if we have: first, the turbine to carry this load; and, second, sufficient steam to drive the turbine at the higher load and higher water rate. The average synchronous turbo-generator is good for two-and-one-half to three times full load on swings. I cannot recall in my experience any case where the overload capacity of the non-synchronous

generator would have any advantage over synchronous turbo-generators.

11. *Strong balancing and damping action.* These characteristics are supposedly of benefit in parallel operation, and probably are intended for comparison with slow-speed synchronous generators. The parallel operation of synchronous turbo-alternators is sufficiently satisfactory for any advantages to be of little value. The damping action has a tendency to correct any irregularities of the sine waves of the system, thus preventing harmonics. This may or may not be an important advantage and requires more thought for a decided opinion than I have been able to give to the subject.

12. *Adaptability to parallel operation, particularly when the prime movers are gas engines.* This is answered, so far as synchronous turbo-alternators are concerned, in the previous statement. I have never had occasion to become sufficiently familiar with gas-engine practice to venture an opinion. I hope to hear this point discussed by others.

13. *When used with synchronous converters is superior to engine driven direct-current generators.* This point appears to be well taken, and I believe here is the field of the non-synchronous generator. Turbine-driven direct-current generators have not proved very satisfactory, and it is doubtful if they will ever be used to any great extent. The slow-speed engine-driven sets are efficient for one point of load and very uneconomical when the load varies through wide ranges. The non-synchronous generator and synchronous converter combination may show sufficient economy to displace engine-driven generators in some stations, and should generally be able to merit adoption when additional power is required.

The disadvantages are:

1. *Inability to furnish a lagging power-factor.* This involves the use of compensating arrangements to neutralize leading currents.

2. *Requires a lagging current for magnetization.* This involves a power-factor less than unity and may generally be considered an unimportant objection.

3. *Requires that the magnetization current be under excellent control.* This is important where there are large overhead or underground distributing systems, as the electrostatic change due to the grounding of one leg will have an immediate effect upon the power-factor.

In systems having long aerial transmission lines and rather high induction, the synchronous converter would have to be considerably over-excited to produce the necessary lagging current for the generator. If an overload should occur, the supply of lagging current would increase; if the overload caused several circuits to open automatically, the induction would instantly fall to a very low value, and unless the power-factor control of the exciting converter were not equally active there would be a rise in potential in the system. This rise would be aggravated if the exciting converter were situated at a substation.

In systems having large capacity in underground cables, either artificial induction would have to be provided or the generators and turbines must be very large. It is shown that the capacity current of the Interborough system would excite a 10,000-kw., 11,000-volt, 25-cycle generator. This would not be a disadvantage if there were not periods of time when the load would be less than half this rate.

I should be pleased to learn if Mr. Waters has considered the possibilities of single-phase non-synchronous generators, particularly the 15-cycle type.

The matter of installation costs has not been gone into very deeply and would be one of the first things to be considered by a designing engineer.

Mr. Stone describes a vertical synchronous converter which appears to possess a number of improvements over the older types. The use of a step-bearing requiring oil pressure lubrication, has been so thoroughly proved practical that we cannot consider it an objection. It appears to me that the greatest objection to this type of machine is the possibility of mechanical damage due to the magnetic pull of heavy armature short-circuits.

The arrangements for changing the pole relations for voltage adjustment are valuable in railway operation where the load conditions change from time to time. The device would not be so important if the generators were non-synchronous.

Mr. Woodbridge dwells at length on the following matters—six- versus three-phase converters, high versus low armature reaction, and compounding.

If the efficiency and maintenance of the two types of converters are equal, or nearly so, the operating engineer cares but little about the fine points of phase relations.

The value of compounding is generally a hard matter to decide. Mr. Woodbridge has discussed this point with commendable clearness.

High armature reaction imparts to a synchronous converter some of the characteristics of the induction motor, and enables alternating-current starting; it also means lower synchronizing power. By lower synchronizing power I mean the inability to stay in synchronism with the generator when the power-factor is low. My experience on a system where both types of converters were used, indicates that an overload condition giving a drop in voltage and sufficiently low power-factor to cause the high armature reaction converters to drop out, would have no effect on the low armature reaction converters.

I was opposed to the induction motor type of starting converters until experience proved that it was sufficient for the service requirements. I have seen a small motor start a 1,500-kw converter four times in succession without trouble, and on the Long Island Railroad system, where the interruptions have at times been rather numerous owing to lightning, there has been absolutely no trouble with the starting motors.

Chas. P. Steinmetz: I fully agree with Mr. Woodbridge. I should, however, consider it still better engineering not to choose the unity power-factor point at half load, but at a still higher load, somewhere between three-quarters and full load. This gives a condition of operation where the wattless lagging current at no load and light load is somewhat greater, though still moderate, but the power-factor at full load and overload is better, and the overload capacity, stability, and reliability greater.

When this type of "split-pole" converter was first brought to my attention, I was not very favorably impressed with it; I rather feared, as result of a preliminary investigation, that this machine would give considerable wave-shape distortions, a poor power-factor and poor commutation, for the same reasons as have been clearly explained by Mr. Lincoln. When the machine was built and tested I was surprised that the bad wave-shape distortion did not materialize. The machine gave a good sine wave, the power-factor was high, and the commutation good. When machine after machine, of various sizes, passed through test into commercial service without showing any wave-shape distortion, or poor power-factor, or poor commutation, I was consoled by hearing that another engineer well known to you all, had also come to the same mistaken unfavorable conclusion regarding this type of converter, and from the same point of view. There is, however, no reason why the machine should not give a perfect sine wave, unity power-factor, and good commutation.

The conclusion from this incident is, that even now it is occasionally desirable to check theoretical reasoning by experimental test, because these two do not always agree, not that the theoretical reasoning is wrong, but because in the premises on which the theoretical reasoning is based, some elements which are essential may not have been given the proper weight.

I am very much interested in the induction generator, for I once believed I had invented it. That was about fifteen years ago; but I found out afterward that long before me, the prominent French engineer, M. Leblanc, had gone over the field thoroughly, experimentally as well as mathematically, and that I was somewhat too late. Considerable work was done afterward by other investigators in developing this type of generator—Bradley, Lamme, and especially by Stanley and Kelly. It has found entrance into technical literature, and performance curves of synchronous motors or converters operated from induction generators are to be found in text-books. In the Standardization Rules of the Institute, this machine and the methods of testing it have been described for ten years. There it is given under its usual name of induction generator. I am sorry to see that Mr. Waters chooses to introduce a new name for this well-known type of apparatus, as this practice only leads to confusion. In the Standardization Rules, the name " induction generator " is analogous to the name " induction motor ", and implies the excitation of the machine by induction; the name non-synchronous machine is rather a misnomer, since the non-synchronous machine is the alternating-current commutator motor, in which the speed has no relation to the frequency. This non-synchronous machine is dependent on the speed for its frequency; it is " near synchronous ", but should no more be called a non-synchronous machine, than a direct-current shunt motor should be called an " inconstant speed motor ", because the speed varies slightly with the load. I do not think it is a good idea either, to name an apparatus by what it is *not*.

This induction generator has not been used to any great extent in engineering practice, due to the limitations imposed by its character. It cannot operate on every kind of load, but requires a load of leading current, or consumes wattless lagging current. The proper field for its use is to supply power to synchronous apparatus, motors as well as converters. I do not need to go into this, because it has been so well discussed by Mr. Waters.

The excitation of the induction generator is supplied by the wattless current delivered by the synchronous apparatus, or by the cables. There are a great many advantages in the use of an induction generator, as discussed in the paper: its greater stability and lesser liability to all those ailments incident to the flow of practically unlimited power in the system, as may occur in the synchronous machine; but it must be realized that naturally there is another side to it. If the disadvantages due to the possibility of unlimited power are eliminated, there are also eliminated the advantages resulting from an unlimited power supply. That means, the voltage regulation of a system with induction generators, cannot be so good as that of a synchronous generator system, for in the last analysis, the voltage regulation of a system depends on the excitation of the system, on the direct-current supply to the fields. In the synchronous-generator-synchronous-converter system there are, as fixed voltage points, the generators as well as the receiving converters. In the induction generator system the only fixed voltage points are the receiving converters, not the generators, and this cuts down the power of voltage regulation to one-half. The trouble of excessive currents is eliminated, but the regulation is somewhat impaired. The use of the wattless charging current of underground cables to help out excitation is an assistance, but at the same time is connected with some serious dangers, because the cables are of constant capacity, and the current taken by them, therefore, is proportional to the voltage. In an induction generator the voltage is proportional to the wattless current received by it, so the machine is liable to build up on its own voltage, just as a direct-current shunt generator below saturation is liable to do. That is, the more excitation is derived from constant capacity, as in underground cables, and the less from synchronous machines, the more fluctuating and unsatisfactory is the voltage regulation of the system. In developing such a system of induction generator operation, there are undoubtedly a number of features and problems which will have to be solved, and which are not always anticipated. For instance, since the voltage depends on the amount of leading current fed into the system, any connecting or disconnecting of synchronous or induction generators, changes the voltage of the system by eliminating the need for so much exciting current, and any converter change, disconnection or connection, changes the voltage of the system. The voltage regulation of the system is taken away from the generating station and located in the converter sub-stations. The latter may be, as pointed out by Mr. Waters, a rather serious feature with a generating station designed for complete voltage control. Such difficulties would be reduced where induction generators are used together with synchronous generators in the generating station.

As to the use of induction generators in a general system of distribution for light and power, probably at 60 cycles, the case stands very much less favorable for the induction generator, due to the large size of its synchronous exciters, for, after all, the synchronous machine must be considered as the exciter of the induction generator, and not the small commutating machine which excites the synchronous machine. Therefore, if the excitation is not given by the load, in using synchronous receiving apparatus, the exciter is rather a big synchronous machine. With high-speed generators of low frequency the exciting current required may be as low as ten per cent. At lower speeds and higher frequencies it is probably nearer thirty per cent. Even if it is only ten per cent., in addition thereto the synchronous exciting machine must also supply all the lagging currents consumed by the system of distribution. A system of distribution for light and power at 90 per cent. power-factor, is possibly above the average. 90 per cent. power factor means 44 per cent. inductance factor, and adding thereto ten per cent. magnetizing current of the induction generator brings the total amount of exciting current up to 54 per cent.; that is, a synchronous machine used as an exciter of the induction generator would be more than half the size of it, rather a large size. This precludes the use of induction machines of the type as described by Mr. Waters for most cases of operating a general system.

In this direction, a very great advance has been made by Messrs. Stanley and Kelly, and was reported and fully discussed in a paper presented by them a few years ago before the Institute. The induction generator has two circuits, the high-frequency circuit supplying power to the outside, and the low-frequency circuit. Instead of applying the magnetizing current to the stator, as the high-frequency member, Stanley applies the magnetizing current to the low-frequency member of the induction generator; and as the volt-amperes required for excitation of the alternating field are proportional to the frequency, by exciting the induction generator, not from the high-frequency stator, but from the low-frequency rotor, Stanley cuts down the exciting volt-amperes from 50 per cent. of the generator capacity to one or two per cent. This requires, then, an alternating-current low-frequency exciter operating at one or two per cent. of the induction generator capacity, a practical machine. In this way, the great objection to the induction generator, of requiring a large synchronous exciter, can be eliminated. The exciter may be a synchronous machine or an alternating current-commutating machine—at such a low frequency as one cycle, or a fraction of a cycle per second, a commutating machine operates very satisfactorily with an alternating field—or an effective capacity as the electrolytic cell, may be used to supply the leading exciting current to the rotor. The interesting self-compounding features of this Stanley induction generator are discussed in that paper.* This method of excitation naturally also imposes certain limitations; it means that the rotor is less simple because currents have to be fed into it from outside sources; it means probably collector rings or direct connection to a generator of low frequency.

There are some very interesting features of the induction generator which have not been mentioned in Mr. Waters' paper; one is that the induction generator does not require a synchronous machine for excitation, but can also be excited by capacity, as the capacity of a cable or an electrolytic cell. The induction generator, then, assumes a characteristic very closely similar to that of the direct-current shunt generator; that is, as the amperes consumed by a constant capacity are proportional to the voltage, and the voltage of the induction generator is proportional to the amperes excitation—if the capacity is too low, the induction generator does not excite, does not energize; if the capacity is sufficiently high, it energizes and the voltage builds up until it passes beyond the bend of the saturation curve and there the machine becomes stable and is a self-exciting alternating-current generator having the same characteristics as the direct current-shunt generator. It shows indeed a very close analogy thereto. The farther beyond the bend of the saturation curve, the more stable the machine becomes. On heavy overloads, especially of lagging current, the induction generator is always liable to lose its excitation; that is, to lose its voltage, just like a direct-current shunt machine, while the synchronous machine will hold up. This may be an advantage, or it may be a disadvantage.

There is, however, one field to which I believe the induction generator is preeminently suited, and that is where water powers are operated in parallel with steam power. In those numerous cases where a water power of limited size is available, and the balance of power beyond that given by the water wheels is supplied by a steam plant, the problem is to take all the load possible from the water power and supply the only deficiency by the steam power. In this case a synchronous machine would be used on the steam engine operating at constant speed, while the induction generator connected to the water wheel would operate without governor on the water wheel—except an excess-speed cut-out. In that case the induction generator speeds up above synchronism until it consumes all the power given by the water, little or much, depending on the conditions. All the power which the water can give is thus supplied to the system; the steam engine supplies the rest. This is a case of parallel operation where a division of load is not desired, but it is desired to take all the available power from one plant, and the rest from the other. To this case the induction generator is eminently suited.

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* Alternating Current Machinery—Induction Alternators, TRANSACTIONS, A. I. E. E., 1905, Vol. XXIV, p. 851.

There is still another field, far broader than anything touched so far, in which the induction generator only can be used and the synchronous generator is out of competition—in the use of an aggregation of small water powers.

There is an enormous amount of power now going to waste; scattered in small creeks and rivers and brooks. There will come a time when the large water powers are developed and used and the problem of gathering the power of all these small streams and creeks will have to be approached and mastered. Only the induction generator can solve the problem. Consider, for instance, one of the numerous little creeks of the New England states, with a limited amount of water, a fall probably of from 200 to 2,000 ft. within 5 to 20 miles. Hydraulic development on present lines there would be out of the question; to bank up the creek, to gather considerable head, and to carry the whole pressure in a pipe-line several miles long would be so expensive as to be impracticable. But there would be a considerable amount of power, if, instead of one of these creeks, there could be combined the power of dozens or hundreds of them. While it would not be economical to develop a single small power, yet where numerous small water powers can be combined it is a practical problem which will have to be solved. The way to solve it, I think, is by building small stone dams across the creek, just high enough to get a supply head of a few feet, to feed into a pipe of a few hundred feet long—ordinary water pipe—and thereby gather a head of some 50 or 100 ft. The water discharges from the pipe against some simple form of hydraulic turbine, and the induction generator is directly connected mechanically to the turbine, and directly connected electrically to the low-tension side of a step-up transformer. The high-tension side of the step-up transformer connects to a transmission line leading along the creek. A number of such small generating stations, which would be simple and cost but little, could be strung along the creek or river, all feeding into the same collecting line. A number of such collecting lines from different creeks could join together in a center of collection. In this manner the total power of all of these streams and creeks could be carried into one central collecting station. The power thus generated and gathered could be distributed to the consumers.

In this field the induction generator is the only feasible type of apparatus. In such a system each station must require no attention whatever beyond a systematic inspection, and must be of the simplest possible character. This excludes synchronous machines with their exciters, switchboards, turbine governors, etc. With a direct-connected low-voltage induction generator, the turbine would run without governor, absorbing whatever power is available, and speeding up until the induction generator slips above synchronism sufficiently to transfer the power to the collecting line as electric current, or; if the line should be idle, broken or so, speeding up to the free running speed, 60 to 70 per cent. above normal. Even the lubrication of the bearings may be by water. The only safety devices would be fuses to cut off the station in case of an accident, which is rather improbable with low-voltage induction machines.

Comfort A. Adams: Although Mr. Waters' enthusiasm has induced a somewhat optimistic point of view, there are certainly many instances where the induction generator is decidedly superior to the synchronous generator. One argument made in this connection by Mr. Steinmetz may leave a somewhat erroneous impression. He cited the case of a lagging load with a 90 per cent. power-factor, where the synchronous exciter would be obliged to supply not only the 10 per cent. exciting current for the induction generator, but also the 43.6 per cent. lagging quadrature current of the load, making necessary an exciter capacity of 53.6 per cent. This sounds like a very bad case for the induction generator; but Mr. Steinmetz failed to state that in the case of this same 90 per cent. power-factor load supplied by a synchronous alternator, the latter would be obliged to supply the 43.6 per cent. quardature current, and that therefore the combined capacity of the induction generator and its synchronous exciter would exceed that of the synchronous alternator by only 10 per cent., the amount of the exciting current of the induction generator.

Concerning that very interesting and puzzling machine, the split-pole converter, I cannot but believe that when we know *all* the facts as to its construction and operation, the apparent gap between the results of theoretical analysis and those of experiment will be reduced to inconsiderable dimensions. Two or three factors which play some part in this explanation have already presented themselves, and will be expanded at a later date, when more information regarding the details of the machine in question is at hand.

One suggestion, however, may be made now; namely, that with a delta connection for the three-phase, or a double delta for the six-phase converter, the third and ninth harmonics disappear, which would considerably reduce the sine deviations tound by Mr. Lincoln for the diametral connection.

J. R. Bibbins: Aside from the purely scientific interest surrounding the theory and application of the non-synchronous generator, Mr. Waters' paper is most interesting, embodying, as it does, the design and experience of a concrete case, which many of us have followed with interest since its installation several years ago. Personally, I am particularly interested in this type of generator from the standpoint of prime-mover design, and Mr. Waters has presented two developments which involved a number of important points. His treatment of the subject makes it reasonably clear that the flexible speed-characteristics of the non-synchronous generator, renders it particularly well adapted to direct connection to prime movers in which cyclic or angular variation of speed is permissible within unusually wide ranges, as in present synchronous generator practice. This feature would, of course, have no bearing upon turbine practice, in which angular variation is absent, but might be taken advantage of in utilizing simple forms of reciprocating engines, such as single-cylinder steam or gas engines.

But in his remarks concerning the modern double-acting gas engine, I believe Mr. Waters' enthusiasm has led him to give an erroneous impression in regard to the possibilities of this type. To obtain the same degree of satisfaction, there does not exist such an ernomous difference between gas and steam practice, either in the matter of flywheels or dampers, as his remarks would indicate. Even if so, the matter of fly-wheels would not seem to be such a serious one, inasmuch as the cost-factor of the iron that enters into fly-wheel construction is barely 30 per cent. of the cost of the finished product in the other parts of the engine. And inasmuch as windage loss is largely occasioned by fly-wheel arms, the increase in loss due to an increased weight of rim would scarcely be noticeable, nor the increase in bearing friction due to the increased weight of rim. It seems probable, therefore, that the 3 to 5 per cent. loss due to friction and damper work ascribed to the gas-engine-driven unit, would not apply to a properly designed machine of the tandem or twin-tandem type.

Philip Torchio: Three years ago a New York lighting company was short of 60-cycle generating capacity, and contracted with a manufacturer for the purchase of a 2000-h.p. non-synchronous generator to be coupled to a 25-cycle motor, for use as a frequency-changer. The reason of this departure was on account of the manufacturer having the frames of the machines, and the company requiring quick delivery.

On account, however, of the impracticability of making the necessary changes in the short space of time available, the proposition was dropped and I am therefore unable to give to-night the actual experience with a non-synchronous generator in connection with a large system.

I endorse what has been said regarding the use of non-synchronous machines in large power stations where the field does not seem to be very promising. I want to call special attention to the figures given by Mr. Waters, where he states that the whole system of 200 miles of high-tension feeders of the New York Edison Company, capable of supplying 150,000 kw., would only supply magnetizing current for a 2000-kw. generator, or less than two per cent. of the station generating capacity.

Regarding the point Mr. Waters makes about the non-synchronous generator reducing surges, I would qualify its practical importance. On an underground system, as of course in any system there are surges whenever the load suddenly changes, while the circuit is closed these surges are not so large as in the case when the circuit is abruptly opened. If the circuit is opened at the instant large currents are flowing, then all the energy stored in the inductance of the circuit oscillates at the period of the circuit between electrostatic energy and electromagnetic energy, and one can figure out that if there were no damping effects due to the resistance of the copper, disastrous voltages might result. As a matter of fact we do not get them, because the oil circuit-breakers open the current at zero or near zero value. I do not see how the conditions would be bettered with induction generators.

Mr. Stone says that to prevent hunting the squirrel-cage coil in the pole tips is the proper thing to use, in which I agree. However, from experience with large systems as operated in New York, it has been found that the ordinary copper grid on the pole pieces has given exactly the same results as the short-circuited coils buried in the iron of the pole tips.

I think it might be well to put on record the *whole year* efficiency of a large system operating over 100,000 kw. of synchronous converters. Including all the losses from the generating station to the low-tension bus-bars of the sub-stations; namely, the losses in transmission lines, static transformers, induction regulators, converters, and all connections—the whole-year efficiency ranges between 90 and 91 per cent. That efficiency has been obtained for several years.

J. B. Taylor: Mr. Clark has well expressed my ideas of Mr. Waters' paper on the induction generator. I concede to this generator two advantages: better mechanical construction and less destructive effects on short-circuits. The other points mentioned seem to be rather in the nature of disadvantages than advantages. The matter of excitation has been already well taken up, and a point I want to dwell on is the fact that the claimed simplicity in the generating station has been obtained entirely at the expense of the sub-station. The sub-station must be ready to start up converters and excite the generators whenever necessary. Just how they would tell when it is necessary, I do not know. It would probably be a matter of establishing telephone communication, and getting the converters under way from storage-batteries, which, if available, have been installed in order to carry the load in times of emergency. These would, therefore, not be in the best condition for carrying the extra load of inverted converters. Then the generating station would have to determine, and bring the generators to, the speed of the converter. If the converters are thrown on to a lagging load, everything may speed up to a dangerous point, since lagging load, as we all know, weakens the field. In other words, there would be a great range between the low speed when connected to cables with leading currents, and high speed when connected to generator with lagging currents.

As more converters are brought to the speed of the system and connected in, more generators can also be connected in. After a time, depending on intercommunication between stations with attendant delays and misunderstandings, all will be in service.

Another point I wish to dwell on is the reference made in the papers and discussion to the disastrous effects of harmonics and departure from sine waves on operating systems. This is an old story, but at the present time I do not know of any case where the wave-form has been shown to be responsible for any case of resonance and where it has been necessary to take steps to change the wave shape or in any way to modify the constants of the system to eliminate this resonance.

There is a story that an old fiddler was playing a violin near a bridge in course of erection. Resenting some personal remarks made about his performance, he started to play, and, finding the note that resonated with some natural period of the bridge, he finally had the bridge shaking so that it would have fallen down if due apology had not been made to him. None of us ever saw such a performance, and never will, for the reason that a violin could not carry sufficient energy to supply the losses incidental to vibration of a bridge structure. Similarly, harmonics on an alternating-current system do not cause destructive resonance, mainly because there is insufficient supply of energy at the harmonic frequency to supply the accompanying losses in copper and iron. If any one knows of a case where an irregularity in the wave-shape of a system, call it the third harmonic or any other harmonic, something due to the wave shape, of the generator, has caused trouble by resonance, I shall be glad to hear of it.

W. L. Waters: Mr. Stone apparently advocates the use of vertical shaft converters, for a number of reasons, but taking the data on these machines as given by him, the reasons do not appear to be sufficiently important for engineers to change their standard type. Taking the 2000-kw., 250-volt converter, which he describes, the horizontal type converter operates at 115 rev. per min., while the vertical operates at 166 rev. per min. The weight given for the horizontal shaft machine is 186,000 lb. The speed has been increased about 45 per cent., while the weight has decreased about 30 per cent. Then again this increase in speed has only resulted in a reduction of about 15 per cent. in the floor space. I would point out that these reductions are obtained just as easily in a more recently designed horizontal shaft machine. This vertical type of machine introduces new uncertainties into the design and operation, this uncertainty being specially the case in regard to the vertical footstep bearing. Roller and ball bearings have been tried for a number of years, but have never been successful for heavy work; and the alternative of an oil pressure bearing depends on maintaining a high-pressure oil circulation. The standard horizontal shaft machine with oil-ring bearings has been in service now for a number of years and there is no doubt about its operation. By the adoption of the vertical type of converter, we are merely introducing extra complication and risks and are gaining practically nothing.

Referring to Mr. Stone's remark on voltage regulation, he describes the method which makes use of a rotating armature alternating-current booster mounted on the shaft between the main armature and the collector rings, and permanently connected in series with the converter collector ring leads. In reference to this, Mr. Stone says that this development "took place abroad," and further that "a few machines of this type have been built by one of the large manufacturing companies in this country". In reference to these statements, I would like to point out that this method of voltage regulation was developed and patented by Mr. C. F. Scott fifteen years ago. and that at the present time there are 10,000 kw. of this type of converter running in New York City alone. The only reason why this method of regulation has not been adopted earlier, is that up till recently it was considered preferable by operating engineers to insert induction regulators in the feeder circuits rather than to vary the converter voltage itself. The objections against this type of machine which are put forward by Mr. Stone are: the extra weight on the shaft, decreased ventilation, lesser accessibility, and increased liability to break down. The extra weight on the shaft is about 15 per cent. and can easily be taken care of. The decreased ventilation is evidently unimportant as the temperature rise on most of these machines as actually built is about twenty degrees on full load. The question of accessibility is unimportant except in the case of repairs or cleaning out the machine.

In regard to repairs, Mr. Stone states that "any serious trouble with this smaller machine results in the dismantling of the main synchronous converter in order to repair the small booster". If Mr. Stone expects ".serious trouble" with this booster wound for 15 volts, it would be interesting to know what he expects to happen to the converter itself which is wound for twenty times this voltage. He proposes as a preferable arrangement that an overhung revolving field booster be supplied. This would mean extra collector rings and extra complication in regard to cables and increased floor space, and in addition we would have a revolving field wound for 125 and 250 volts instead of a revolving armature wound for 15 volts. Referring again to the question of floor space, I would point out that as the distance between bearing centers in a horizontal shaft converter is to a great extent decided by questions of mechanical stability, there is practically always space enough between the armature and collector rings to insert a revolving armature booster. In any case, the extra length along the shaft necessary to take care of such a booster would not exceed 10 in. or 12 in., while the extra length required for a revolving field booster would probably be 2 ft. to 2 ft. 6 in.

The question of six-phase versus three-phase is entirely a manufacturing rather than an operating engineer's question. It is to be decided by which is the cheaper machine in any individual case. The great advantage of a six-phase converter is, as Mr. Woodbridge has pointed out, that it saves armature copper. There has been a tendency on the part of some manufacturers to pay more attention to theoretical considerations than to operating conditions when deciding the amount of copper to be put on the armature of the converter. It was often decided because the total armature copper loss in the six-phase converter was only one-quarter of that of the corresponding direct-current generator, that it was advisable to reduce considerably the section of copper in order to reduce the cost. This method of designing was finally stopped by the operating engineers themselves, who refused to take converters with such small sections of copper, having found by experience that theoretical considerations were not always verified in practice. At the present time it has been shown that the only way to design converters for heavy service is to allow ample copper on the armature, and that it is advisable to design the machine irrespective of whether it is to operate three-phase or six-phase. Further, the question of using the extra three collector rings as balancing rings for the armature is again a manufacturer's question. If we want more balancing rings on a converter, they can be put on without regard to the collector rings. And in a large number of cases the extra three collector rings and cables are merely an unnecessary complication, this being especially the case in 60-cycle converters where the section of armature copper is decided by mechanical reasons, and where the current density is very low. Mr. Woodbridge's statement, " but in any event a three-phase machine may be safely increased in rating some 40 or 50 per cent. . . . by the addition of three more collector rings " hardly needs criticism, as any engineer who has designed or operated modern converters knows that it is not the heating of the armature but the sparking or flashing at the commutator that decides the rating of a converter, and these are not influenced by change from 3-phase to 6-phase.

Taking the question of starting converters, the method advocated by Mr. Woodbridge which is direct application of alternating current to the armature windings through the collector rings, can only be applied satisfactorily on machines with either no dampers on the pole faces or else with only very light dampers. The reason for this being that with heavy dampers there is flashing at the commutator when starting. If we are willing to endure hunting of the converter on light loads or on certain conditions of the circuit, then we can run with light dampers and start up in this way. In any case, however, this method is not a good one from the operating engineer's point of view. Taking Mr. Woodbridge's own figures, it takes from two-thirds to three-fourths the normal rated kilovolt-amperes to start the converter in this way. The power-factor of this current will be about 20 per cent. If we have an induction motor for starting the converter, this motor will take about 30 per cent. of the full rated kilovolt-amperes of the converter when starting, and this current will have a power-factor of about 80 per cent. Thus with a starting motor we take wattless kilovolt-amperes equal to 18 per cent. of the normal rated kilovolt-amperes of the converter, while starting directly from the alternating current side of the converter armature we take wattless kilovolt-amperes equal to 70 per cent. of the normal kilovolt-amperes; that is, starting as advocated by Mr. Woodbridge takes four times the wattless kilovolt-amperes which would be required with a starting motor. The watt kilovolt-amperes taken from the system is unimportant in either case, because it is always the wattless amperes which upset the regulation of a system. These figures show us at once, why, if a large converter system is shut down, it takes so long to get the system started again when we try to start the converters from the alternating current side. Mr. Woodbridge states that the converters would not start up simultaneously so that the power station could carry the wattless load satisfactorily. We might add to this that in certain cases where they have tried to start up simultaneously the power station has been unable to keep the voltage high enough to start the converters.

The two most reliable methods of starting converters are:

1. An induction motor wound for slightly higher synchronous speed than the converter and with a high resistance secondary. The induction motor is thrown directly on the full alternating

voltage, and as the machines come up to speed the main alternating current switches are closed through a resistance. This resistance limits the synchronizing current and enables the machines to get in step quietly. The resistance is then short-circuited and the induction motor circuit opened.

2. A small induction motor-generator starting set installed in the sub-station, this being used to start the converters from the direct-current side.

These two methods, one for starting from the alternating-current side and the other starting from the direct-current side, are undoubtedly the most reliable methods of starting a converter. The method advocated by Mr. Woodbridge requires extra complication of cables and switches, and extra taps on the transformers. It will, however, usually work out that Mr. Woodbridge's method is cheaper and it is a question for the operating engineer to decide as to whether he prefers cheapness in first cost or reliability of operation.

I think that it is pretty evident that there must be *some* distortion of wave-form when the voltage ratio of alternating current to direct current in a converter is varied by the split-pole method; the only question is to what degree the wave-form is distorted. Mr. Steinmetz says that a sine wave is obtained under all conditions of voltage ratio. I think, however, he must be speaking in a general way, because it is evident that a pure sine wave can only be obtained when the distribution of magnetism also follows a sine wave which cannot possibly be the case under all conditions of voltage ratio in a split-pole conververter. I would point out that the power-factor as obtained on a power-factor meter would give no indication of such distortion, as a power-factor meter does not take into account the higher harmonics. Possibly Mr. Steinmetz forms his opinion from oscillograph records taken from such converters. I would like to point out that the average commercial oscillograph is, comparatively speaking, an incorrect instrument, and that its record depends to a great extent on the various adjustments of the instrument. So that unless extreme precautions are taken by an experienced and skilful operator, I would rather take the calculated wave-forms than those obtained by an oscillograph. A very simple way to show that distortion is present is to measure the power-factor of the converter running light from the direct-current side and under different conditions of voltage ratio, such power-factor being measured by taking readings of volts, amperes, and watts. I think such a power-factor reading will show at once that very considerable distortion has taken place.

Mr. Clark's criticisms are conservative and well taken, and are generally such as we would expect from experienced operating engineers when such a comparatively new proposition is put before them. He refers to the size of the air-gap on this type of machine. The clearance between the rotating and stationary part varies from $\frac{1}{8}$ in. to $\frac{1}{4}$ in. He refers to the use of non-synchronous generators for 15-cycle single-phase traction power generation. The non-synchronous generator would be an especially good machine for such work, so long as the power-factor was not too low. Usually the power-factor in such a station can be kept about 85 per cent., and in such a case the non-synchronous generator would compare very well with a synchronous machine. It would behave considerably better than a synchronous generator on short-circuits, and would be less liable to damage, and for such a low frequency could probably be designed to be quite a little cheaper. The wattless current would, of course, in this case have to be supplied by high-speed synchronous motors running light in the power station. Mr. Steinmetz objects to the size of the synchronous motor necessary to employ in order to supply the wattless current in a system of non-synchronous generators. I would point out that each case must be considered in itself, and in the case of the gas-engine-driven station described there are 3500 kw. non-synchronous generators each requiring a 4500-kw. synchronous motor, and yet this station proves to be a commercial proposition. The size of the synchronous motor is immaterial so long as the first cost, maintenance and efficiency do not prove unfavorable.

Referring to the other non-synchronous motors mentioned by Mr. Steinmetz; namely, those of Stanley and Heyland, these were not mentioned in the paper as they were hardly considered commercial machines. The necessity for a coil winding and collector rings, on the rotating part, takes away practically all the advantage of simplicity in construction which the non-synchronous generator possesses. Such machines would hardly be considered for American power station work.

J. E. Woodbridge: Mr. Clark made a statement to the effect that as long as converters operate satisfactorily, a difference of a few per cent. more or less in power-factor is immaterial. This is true if the machines do operate satisfactorily, but a few per cent. difference in power-factor occasionally makes the operation quite unsatisfactory. A case has recently been reported where a converter smoked badly on a guaranteed overload. When this converter was run at unity power-factor it carried the same overload for a greater length of time with a temperature rise of only 30° cent. As I stated in my paper, railway converters work, as a rule, under such low load-factors, and are designed for such heavy overloads, that a few per cent. more or less in power-factor gives no trouble, but when converters are worked near their guaranteed loads the power-factor is relatively important.

Mr. Clark also referred to the low "synchronizing power" of converters with a high ratio of armature to field ampere-turns as compared with those of a lower ratio, and spoke of machines with the former characteristics dropping out of step on loads which the other machines would carry. My experience has been limited to railway work where machines are normally protected by circuit-breakers, and I have never heard of a case of a machine being pulled out of step by load. If the circuit-breakers are blocked, the alternating-current automatic protection, whatever it may be, unless also blocked, will operate on sufficient overload, and it is impossible to state whether this automatic protection is due to the load or to falling out of step on the part of the converters. I believe no case of this kind can be substantiated, with the exception of loads so great as to drop the voltage to zero, that is, short-circuits.

Mr. Waters gave a figure that I wish to dispute, namely, the power-factor of the starting currents of converters. With converters with narrow air-gaps, high armature reaction, low field densities, and with short-circuiting pole-face windings, I am positive that the power-factor of the starting currents is much higher than the 20 per cent, which he gave, although I have not made any direct tests on this point. For one reason, 20 per cent. would not, as a rule, give sufficient torque to start the converter in all cases, allowing for no losses or any kind whatever. A test which I do remember, showed a starting current of roughly 1500 amperes in the secondary connections which went down to 300 amperes magnetizing current when the machine reached full speed and before the field was excited. This indicates a power-factor at the converter approaching 98 per cent., but the magnetizing component was undoubtedly somewhat greater, due to the influence of the currents in the pole-face windings at lower speeds. I think that the power-factor can be safely stated to be somewhere between 70 and 80 per cent., which compares favorably with the power-factors of starting induction motors.

The input of a starting induction motor is not so greatly different from that of a self-starting converter with the characteristics described in the paper; for example, a 1500-kw. converter which I was watching this afternoon required 400-kw. for starting by means of an induction motor.

With regard to the recommendation of Dr. Steinmetz, that transformer and converter voltages should be so proportioned that compound converters would reach unity power-factor at about full load, such a radical departure from existing practice was more than I dared to suggest. Experience indicates that when transformers give such a high secondary voltage as to meet this condition, thereby giving an abnormally high direct voltage at no-load unity power-factor, either the operators run at that voltage and are glad to get it, or run at that voltage and grumble at it, either of which condition is rather unsatisfactory. With transformer ratios designed to give unity power-factor at full load, with a representative amount of resistance and reactance in circuit, unity power-factor at no load gives about 10 per cent. over voltage; that is to say, a 600-volt converter would run at no-load unity power-factor at 650 to 660 volts. To force it down to rated voltage at no load would require an alternating-current lagging input at no load amounting to 50 to 80 per cent. of the rated full-load current of the converter, according to the strength of the series field. I believe few operators would properly handle an equipment of this kind. They would simply run 5 or 10 per cent. above voltage.

C. W. Stone: If all the statements just made by Mr. Lincoln and apparently seconded by Mr. Scott were borne out by the facts as demonstrated by the machines which have actually been built and tested, I should feel that I had made a grave mistake in coming before you and calling to your attention this new type of machine.

It is possible to calculate results which will approximate those that Mr. Lincoln has also reached. However, consideration must be given to other conditions which are apparently overlooked by Mr. Lincoln. The curves shown by Mr. Lincoln are evidently only calculated curves, and not oscillograph curves taken from actual machines. I am sorry that I did not have time to prepare some oscillograph curves which were taken across the collector rings of one of these converters, working through an extreme range in voltage. These curves approximate a sine wave. The higher harmonics mentioned by Mr. Lincoln are not apparent.

Some question was raised about the change in excitation of the main fields in order to maintain minimum current input to the converter. As a matter of fact, the main field excitation, when the load is constant, varies less than 5 per cent. for the extreme ranges in voltage; that is, from the full bucking to the full boosting voltage obtained by exciting the auxiliary field—this on a machine on which was obtained a range in voltage of approximately 175 to 350 volts, the normal being 250 volts.

Some long-continued test-runs were made on machines of various sizes, and it was found that they were all within the heating limits usually specified, and considerably below the guarantees made.

In reference to the cost of the converter built according to the Woodbridge design. In designing a 2000-kw. machine, I had a number of different designs made up to get a comparison of the cost of this type of converter with a converter using an induction regulator; I was unable to find that the converter would cost any more than a converter with an induction regulator built for the same range in direct voltage, the range in voltage being from 200 to 300 volts with normal voltage of 250 volts.

Mr. Lincoln thinks that on account of the wave distortion the converter might have a serious effect on the other apparatus operating on the system, and that in all probability the results obtained in test would not be reproduced when the machines were connected to the operating systems. In order to verify my opinion, I had the machines operated from small machines, from large machines, and in fact from all types of machines, including motor-generators, engine-driven generators, turbine-driven generators, alone and in parallel; with the same excitations the same voltages were obtained, the curves agreeing exactly, irrespective of the type of apparatus or the size of the system on which the converter was operated.

The first machine built for investigating the Woodbridge method of voltage control was made by taking a standard converter, the field spools of which were removed and replaced by some field spools made up of three sections each, on each section of which were placed the two windings in accordance with the Woodbridge scheme. The wisdom of the idea was demonstrated by the operation of this machine. The machine has been in commercial operation considerably for more than a year, and no trouble has been experienced although it has been operated under very adverse conditions.

It is true that in order to obtain the necessary space for the extra field spools, it is necessary to increase somewhat the diameter, and consequently the weight, of the whole machine; but the increase in cost of the converter due to this extra material will just about offset the cost of the induction regulator. I think I am safe in predicting that, after the idea is a little better known, and a little more experience has been had in the manufacture of these machines, there will be still further reductions in the cost.

Referring to the converters using the booster control system, I would say that I have had machines designed both with the revolving armatures and revolving fields. I have compared the cost of these machines with the cost of standard converters using induction regulators and converters made in accordance with the Woodbridge idea, and also converters made in accordance with the Burnham idea. I think that without question the converters built in accordance with the Burnham scheme will be as inexpensive as any.

The question of which type of machine, the revolving armature type of booster or the revolving field type of booster, is the better, I shall not discuss. I think that the revolving field type is the better, but this is a point upon which engineers will necessarily disagree; and in view of the new developments with the Woodbridge or Burnham type of converter, I think this whole question will be eliminated.

Mr. Waters says that roller bearing, used with the vertical type of converter is an old idea, but nobody has been able to make them work satisfactorily. I might say that the type of bearing used in this machine has been in use at Niagara Falls for several years on the Niagara Falls generators, having approximately 30 per cent. more weight and operating at 50 per cent. higher speed. No trouble whatever has been experienced with them.

J. B. Taylor (by letter): The proposed system using induction generators relies largely on converters for excitation, which means that these latter machines must run at power-factors other than unity. These machines as ordinarily designed are not well adapted to run at low power-factor, the increased and localized heating under these low-power factors being ably explained in Mr. Woodbridge's paper.

Too great advantages are claimed for the ease of paralleling induction generators. While exact synchronism and phase relations are not essential for paralleling induction generators, it is essential to have the speed nearly correct. For example, if the slip to give full load is one per cent., a difference in speed of two per cent. when paralleling will immediately subject the machine to twice full load, either as a motor or as a generator, and devices must be provided to indicate the proper speed. Tachometers on the machines can not, in general, be depended on to a fraction of one per cent.; even with suitable tachometers, these are not readily seen by the switchboard attendant, who is the person most interested in knowing when speed is correct. Devices to show synchronous speed on induction motors have already been devised and placed in service, but these devices can not be regarded as any simpler than the usual form of synchronism indicator used with synchronous generators. The proposal to connect generators to line, first, through reactive coil, and then cut out the reactive coil, calls for additional apparatus and switches with additional complication in manipulation; means for adjusting load by pilot motors is already a well worked out device for synchronous machines.

In discussing the split-pole converter, Mr. Lincoln has shown a number of curves of calculated flux distribution and accompanying waves of electromotive force. His general objections to this type of machine on the score of power-factor, wave-shape, and efficiency have been satisfactorily answered by others who have shown that " the best proof of the pudding is in the eating ", since the terrible distortions and losses anticipated have not been found in actual test. Mr. Lincoln's curves, I believe, were all based on a diametrical voltage, and do not hold for the three-phase converter or six-phase converter connected double delta. The final effect of possible third-harmonic voltages or third-harmonic currents in the system will depend largely on combination of converter and transformer connections.

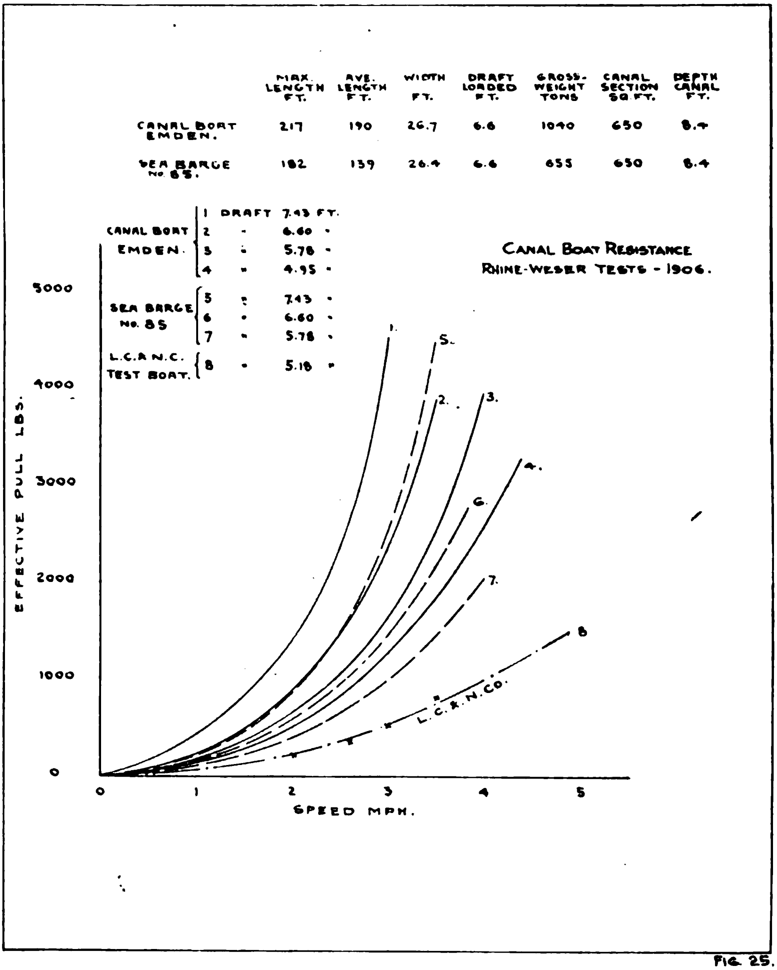
Mr. Lincoln properly points out the distinction between true power-factor and power-factor as indicated by certain types of instruments which show merely the cosine of the angle of lag rather than ratio of true watts to volt-ampere product. The case commonly referred to in bringing out this point is that of the alternating-current carbon arc, where current and voltage at the arc are in practically the same phase relation, with no angle of lag, and true power-factor is far from unity, on account of the fact that the two wave-shapes are not alike and maximum value of current does not coincide with maximum value of potential. It seems proper to point out here that the principal objection to low power-factor is the demagnetizing action on generators. For low power-factor due to wave-shapes rather than to angular displacement between current and electromotive force, the demagnetizing objection does not hold.

NOTES ON ELECTRIC HAULAGE OF CANAL BOATS.

BY LEWIS B. STILLWELL AND H. ST. CLAIR PUTNAM.

APPENDIX.

The tests conducted on the Lehigh Canal were for the purpose of determining the practicable towing speeds and the power required to pull a boat of the type used on that canal. A general investigation of canal-boat resistance was not attempted. It is of



	MAX. LENGTH FT.	AVE. LENGTH FT.	WIDTH FT.	DRAFT LOADED FT.	GROSS-WEIGHT TONS	CANAL SECTION SQ. FT.	DEPTH CANAL FT.
CANAL BOAT EMDEN.	217	190	26.7	6.6	1040	650	8.4
SEA BARGE No. 85.	182	139	26.4	6.6	655	650	8.4

FIG. 25.

FIG. 25

interest, however, to compare the results obtained with the results obtained in the very complete tests made by Sympher, Thiele, and Block on the Rhine-Weser Canal in 1906. In Fig. 25 we have reproduced the results of these tests, as well as the results obtained on the Lehigh Canal.

The Rhine-Weser curves indicate that the clearance between the bottom of the boat and the bottom of the canal is most important as affecting canal boat resistance. In Fig. 26 we have plotted the results of one of the series of Rhine-Weser

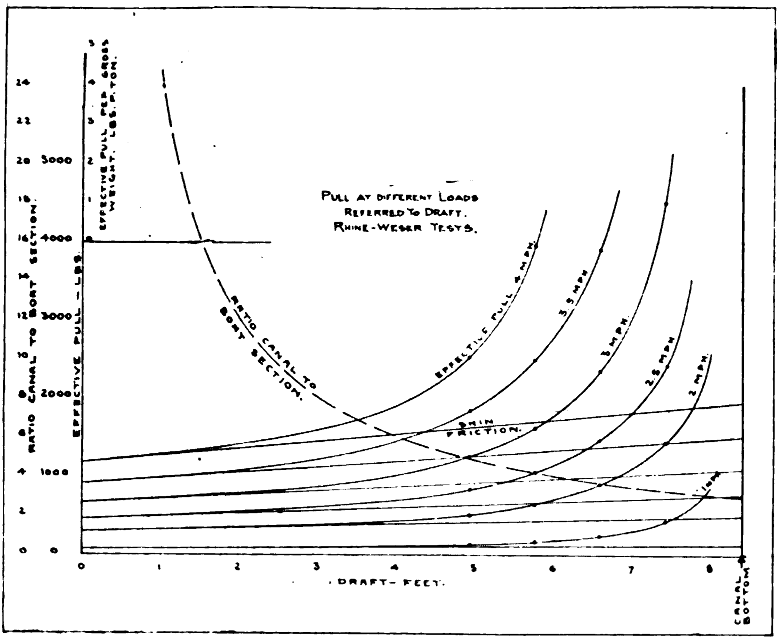


Fig 26

FIG. 26

tests in terms of draft and have deduced the skin friction from the Lehigh tests. This gives a point which permits the extension of the curve to zero draft with approximate accuracy. It will be noted that with a constant speed the resistance bears but slight relationship to the ratio of canal to boat cross-section, but is affected to a much greater extent by the clearance between the boat and the bottom of the canal.

In Fig. 27 we have plotted the difference between the total friction and the skin friction in terms of resistance per square foot of bottom surface as related to the clearance below the bottom of the boat. The points shown are from two tests, the boats in each case having the same cross section but different lengths and differently shaped bow and stern. The results show a fairly close agreement in the unit of resistance as referred to the bottom clearance. It is unfortunate that the tests did not include boats of the same draft but with different bottom clearances, but the data obtained indicates the importance of the clearance below the bottom of the boat, a point that until recently has been generally overlooked in canal work.

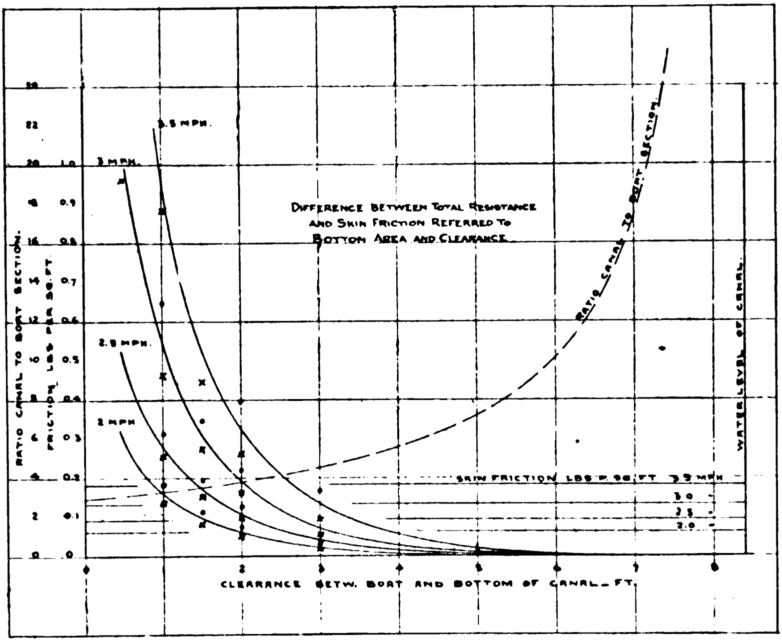


FIG. 27

An interesting point brought out by this method of plotting the test results is that the sea barge No. 85, with the same cross-section as the canal boat Emden, but with a length of 182 ft. instead of 217 ft., shows the smaller unit resistance as referred to the bottom clearance. The increase in unit resistance in case of the longer boat is probably due to the reduction in bottom clearance on account of the settling of the boat and the angle assumed by it relative to the general surface of the water under speed conditions. If the angle is the same in both cases, the stern of the longer boat will be brought closer to the bottom than will that of the shorter boat, with the result that the effective bottom clearance will be reduced. It will be noted that this effect is most marked at higher speeds, as we should expect to be the case.

As a matter of interest, the unit values in Fig. 27 have been applied to the boat as tested on the Lehigh Canal, the average bottom clearance being estimated at 1.57 feet, and the ratio of canal section 8 to 1 as compared with 3.6 to 1 as existed with this clearance in the Rhine-Weser tests. The resulting points are shown in Fig. 25 and closely agree with the test results.

In Fig. 28 we have plotted the total pull per ton required at various uniform speeds and with different drafts. These curves show that for a given speed there is a load at which the pull required per ton is a minimum, and that the pull required per ton increases rapidly as the clearance beneath the boat is diminished beyond a certain point. A relatively small clearance is permissible at low speeds but at the higher speeds which can be attained in mechanical towing the bottom clearance must be carefully considered.

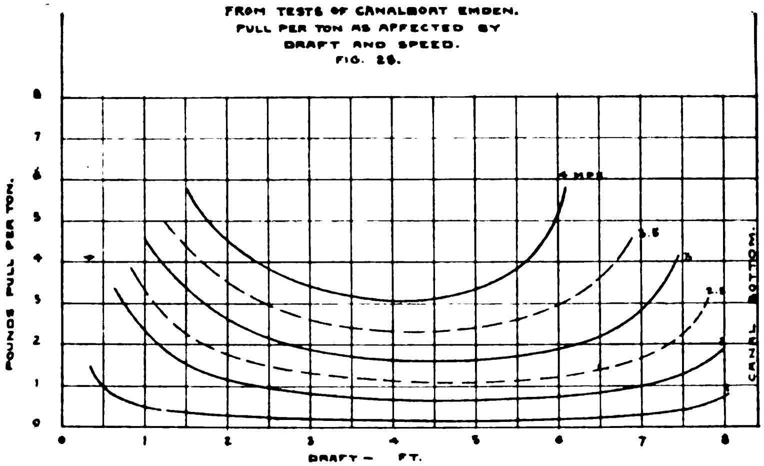


FIG. 28.

The important fact brought out by the curves plotted in Fig. 28, is that the power required to tow a canal boat at a given speed is a minimum per ton of gross weight when the draft is approximately one-half the depth of the canal. The curve of resistance at a given speed with different drafts closely approximates a hyperbola; and a hyperbola, representing the resistance, divided by a straight line, representing the tonnage as referred to draft, gives a minimum at one-half the depth of the canal. The same law probably applies to the width of the boat as compared with the width of the canal. With data of similar character and with known cost of power, crews, and canal-boat maintenance, the most economical type of boat and speed for a given canal can be determined.

DISCUSSION ON "THE EDUCATION OF THE ELECTRICAL ENGINEER", AT NEW YORK, JANUARY 24, 1908.

(Subject to final revision for the Transactions.)

Charles F. Scott: Since preparing this short paper which I intend to present this evening, I have taken part in a symposium on "The Teaching of Mathematics to Engineeers", at a joint meeting of the Chicago Section ot the American Mathematical Society and the Mechanical Section of the American Association for the Advancement of Science. My contribution seems to me so pertinent to the educational questions now under consideration that I shall present it here.

Mathematics, from the standpoint of the engineer, is a means, not an end. It is an instrument or tool by which he may determine the value and relations of forces and materials. The usefulness of tools depends upon the sort of work which is to be done, upon the kinds of tools which are available, and upon the skill of the man who uses them. We may inquire, therefore, what are the uses to which the engineer may apply mathematics? What kind of mathematics does he need? And what skill should he possess in their use?

First, then, what work is to be done by the young men who are now taking engineering courses? A few—and only a few—will be original investigators or designers who will need mathematics as an instrument of research. A considerable number will regularly employ elementary mathematics in more or less routine calculations. Many will have little use for mathematics, as engineering courses are recognized as affording excellent training for various business, executive, and other non-technical positions, particularly in connection with manufacturing and operating companies. It has been said by the vice-president of a large electric manufacturing company that not over 10 per cent. of the technical graduates employed by that company are fitted by temperament or by education to take up with success the work of pure engineering. A recent classification of the graduates of Sibley College, Cornell University, shows that about 50 per cent, are in occupations which require no advanced mathematics, and it is probable that many of the 36 per cent. classed as mechanical and electrical engineers seldom go beyond the rules of arithmetic. Hence a goodly proportion of engineering graduates do not need to be mathematical experts. Their mathematical studies should not aim to produce experts, but should have as a principal object the mathematical training which is a most efficient kind of training in an engineering course. On the other hand, the engineers who will have practical use for the higher mathematics will find their ability as engineers is in a large measure determined by their ability as mathematicians.

Secondly, what kinds of mathematics does the engineer need? This is closely related to the class of work he is to do. In general, a great deal of engineering work is done with much less use of higher mathematics than most professors probably imagine, and furthermore, it may be remarked, with much less than could profitably be employed. Engineers are apt to use ordinarily the mathematical methods with which they are most familiar and which will bring the result with the least effort. One man employs calculus, another draws a diagram, another writes out formulas, while still another gets his results by mental arithmetic. The object is to get the result. The fundamental idea that mathematics is something for the engineer to use finds many illustrative analogies in ordinary tools.

Adaption is the first requisite; tools should be suited to the work to be done. An expensive machine-tool with its refined adjustments is quite unnecessary for executing a piece of work which can be done with sufficient accuracy by a few minutes' application of a file. In every-day work an ordinary calculating slide-rule is infinitely better than a table of seven-phase logarithms. On the other hand, it is particularly wasteful to attempt to execute a difficult and intricate piece of work with inadequate tools. But more important than the tool is the skill of the man who uses it. A skilful workman can accomplish results with a few simple tools which another cannot get with the most elaborate special equipment.

Thirdly, therefore, skill in the use of mathematics is the really essential thing. A judicious use of arithmetic with a little algebra or a simple diagram often leads to more satisfactory results than others obtain through elaborate processes involving lengthy equations and complicated operations. In the latter, errors are liable to occur; the common-sense import of the problem is apt to be overlooked; assumptions may be made to facilitate calculations which are physically unwarranted, as one loses sight of the physical problem in the intricacy of the mathematical solution. Abstract mathematical studies, if pursued as a kind of intellectual calesthenics, may produce a pure mathematician, but they may unfit a man for practical engineering. A mathematician is not necessarily an engineer, nor is an elocutionist necessarily a good lecturer, nor a tool expert a successful manufacturer.

Mathematics is used in engineering to express the quantitative relations of natural phenomena. The mathematician delights in the relations; he divorces them from the phenomena and gives them abstract expression. But the engineer is concerned with the natural phenomena; he demands the physical conception; the medium of expressing these relations is of secondary consequence.

The mathematician evolves the equation for a parabola and finds a convenient illustration in the law of projectiles. The engineer finds that a physical result follows from the application of certain forces, and uses the formula merely as a convenient method of expressing the law. The analogue in the case of mechanical tools is found by regarding a set of drawing instruments or a transit or a lathe, as something intelligently designed, properly proportioned, accurately made, and finely finished, the merit of which lies in their own inherent excellence, or, on the other hand, by considering them as tools adapted for doing a certain range and character of work with a sufficient degree of accuracy and at low cost.

A manual training school gives familiarity with mechanical tools, and mathematical study gives familiarity with intellectual tools. In working with the manual tool, the boy uses it for making something; by making something, he learns the principle on which it operates and the way to use it. If the thing made is something useful, it awakens a keener interest than perhaps would some fancy device. Likewise training of engineers in mathematics should be by doing something, by the solving of problems, by dealing with real rather than abstract conditions. Let this training be obtained while applying mathematics to its normal and legitimate purpose as an auxiliary to the study of other branches.

In the teaching of mathematics for its own sake stress is apt to be laid upon the processes of deriving results rather than the real meaning of the results themselves. An engineer who uses logarithms has no more concern regarding their derivation than the ordinary user of the dictionary for finding the pronunciation of words has in their etymological derivation. The ability to reproduce demonstrations in higher mathematics from memory with the book shut is often not as important as it is to understand them with the book open. In general, an engineer who has occasion to use higher mathematics, will not be interested in evolving difficult equations, nor will he appeal to his memory; but with text-book or reference before him he will seek the things he wants to use. He should know where to find them and how to use them.

In emphasizing what a skilled mechanic can make with very ordinary tools, or the true engineer can accomplish with the parallelogram of forces and the rule of three, there is no intention of discrediting the value of fine equipments both mechanical and mathematical if there be the ability to use them.

Possibly the practical utility of mathematics may appear to be urged too strongly, particularly as the writer really believes in thorough mathematical training; but he has seen so many cases in which mathematical instruction has never been digested and assimilated, so many simple mental processes confused by unnecessary mathematical complications, so many men satisfied with results which are absurd because of some mathematical equations, sometimes quite unnecessary—that a common-sense perspective view of ordinary things seems to need emphasizing. He recalls the new insight into mathematics which came through the study of analytic mechanics under Professor S. W. Robinson at the Ohio State University, and problems in mechanics under Dr. Fabian Franklin at Johns Hopkins University, that he feels there is little danger in over-emphasizing the importance of concrete training in mathematical study.

The practical questions which the discussion of this subject presents are these:

1. What mathematical subject-matter should be covered?
2. How should it be taught?

The first difficulty is that there is not, and cannot be, a differentiation in technical education which is at all comparable with the wide range of occupations into which graduates will enter. We may assume, therefore, that we are considering the case of the average engineering student, taking for granted that options may be used by the best students to enable them to take up the more advanced and difficult mathematics. Obviously, the student should have enough mathematics to enable him to demonstrate the important engineering laws and formulas, and to read intelligently mathematically written engineering literature. While only the relatively simple mathematics is commonly used by engineers, yet the ability to handle new problems with confidence requires a thorough understanding, and appreciation of the significance of the mathematical and physical basis of the laws and phenomena he is to use. A man who is a thorough mathematician and knows how to apply his knowledge has a great advantage over the pure mathematician or the man without mathematical training. The better knowledge one has of the complex, the more certainty he has in applying the simple. A student should understand something of the power of the advanced mathematics and the field of their efficient application. Although he may not be expert in using them himself, he will know when to call for a mathematical expert.

An engineer of fairly wide experience remarked a short time ago:

> The ordinary engineer does not use higher mathematics because he doesn't know how. He does not have the proper conception of the fundamental principles of the calculus because the subject has been taught by men whose ideals are those of pure mathematics.

If mathematics is something for engineers to use, let their use be taught to engineering students. After the fundamentals are learned, the students should attack the engineering problem at once and bring in mathematics as a means of solving it. Mathematics is often advocated for developing the reasoning powers and the ability to reason from cause to effect; there is danger, however, that mathematical machinery may make the mere process obscure the cause and the effect. Let cause and effect be foremost, with the process secondary or auxiliary to them. The way mathematics is brought to bear on some engineering problems reminds one of the story of the old lady who greatly admired her preacher because he could take a simple text and make it so very complicated.

Old traditions have not wholly disappeared; the fear of de-grading the pure science of mathematics by applying it to useful things still lingers—in influence, if not in precept. We must go further and adapt mathematics to engineering, not only in subject-matter, but in method. A mathematical teacher with no patience for anything except mathematics will probably teach a kind of mathematics which has no connection with anything except mathematics. Engineering mathematics may be better taught as a part of engineering by an engineer, than as a part of mathematics by a pure mathematician. The maker of levels and transits who is expert in the construction of the instruments and an enthusiast over the accuracy of the surfaces, the excellence of the bearings, the near approach to perfection in the graduation, and the general refinement and beauty of workmanship, may make a good instructor on instruments, but a poor teacher of civil engineering.

After all, it is not so much abstract courses as it is men with which we have to do; it is not mere knowledge of facts or facility in mathematical manipulation, but it is training. The young man is to be developed; his native individuality is to be the basis; he is to increase not only his knowledge but his powers and the ability to use them. It is not mathematical skill so much as a mathematical sense, or mathematical common-sense, which is wanted. With pure mathematics as a science we have no quarrel—and little affiliation.

We are concerned with applied mathematics. The ability to state a problem; to recognize the elements which enter into it; to see the whole problem without overlooking some important factor; to use good judgment as to the reliability or accuracy of the data or measurements which are involved; and, on the other hand, the ability to interpret the result; to recognize its physical significance; to get a common-sense perspective view of its meaning and the consequences which may follow; to note the bearing of the various data upon the final result; to determine what changes in original conditions may change a bad result into one which is practical and efficient—such abilities as these are of a higher order than the ability to take a stated problem and work out the answer. It may be urged that all this is not strictly mathematics. But it is just this sort of judgment and insight which makes mathematics really useful, and without them there is danger that they may be neither safe nor sane.

If you ask men who use engineering graduates what qualities they should possess, you will find that special prominence is "common-sense" and "the ability to do things." In mathematical training it is quality rather than quantity which is of first consequence. Mathematical training should develop a faculty for systematic and logical reasoning, thus furnishing a general method as well as a specific means of getting results.

The trend in education is to a closer relation to the affairs of life. Science and applied science, scientific and engineering laboratories are overcoming old ideas and prejudices. Modern engineering development brings its transforming influence to bear upon education as well as the utilities of modern life. The engineering school has had a phenomenal growth within the lifetime of the recent graduate—a growth in ideals and methods as well as in students and equipment. It has raised and agitated broad questions as to what constitutes efficient education for producing effective men. It has aimed to combine not only the abstract with the concrete, the lecture room with the laboratory and the scientific experiment with the practical test; but it has sought by various means to bring the work of the school into close relation with active professional and commercial practice. It has a definiteness of aim and purpose which other educational courses are apt to lack. It sets out to produce men who can deal with forces and materials according to scientific principles. It develops men whose contact with physical facts and natural laws at first hand and whose ability to reason logically fit them for dealing with new problems. The training which fits men for handling engineering problems is the kind that is needed for dealing with the organizing and directing of men. The sphere of the engineer is one the scope of which will continue to increase as engineering education and training produce men whose contact with natural phenomena gives them an inherent respect for facts as their premises, who are able to think straight to logical and common-sense conclusions, who have an equipment of technical knowledge and who can produce results.

In discussing the teaching of mathematics to engineers, we should emphasize not the mathematics nor the engineers, but the teaching. Aside from the imparting of knowledge and technical ability, the teaching of mathematics gives opportunity for training in the use of logical methods and in the drawing of intelligent conclusions from unorganized data which will make efficient men, whether they follow pure engineering or semi-technical or business pursuits. Such teaching does not come from the text-book; it must be personal—it comes from the teacher. He must be in sympathy with engineering work and have a just appreciation of its problems and its methods. He must be imbued with the spirit and the ideas of the engineer.

Chas. P. Steinmetz: I agree with Mr. Scott in the relation of mathematics to engineering. I agree with him also that mathematics is a tool, the most important and useful tool of the engineer; but it is useful and valuable only as long as it is a tool, and ceases to be useful as soon as it goes beyond a tool and becomes a purpose. Mathematics becomes not only useless but positively dangerous as soon as the user does not fully and clearly see the physical meaning of every mathematical step he takes, or fully appreciates the physical meaning of every step when reading through a mathematical derivation of a result. As soon as one understands the physical meaning of every step, one can, as a rule, greatly simplify the mathematics by skipping complex mathematical reasonings by a short cut based on common-sense. For instance, instead of carrying the calculations through with the positive and negative signs of a square root, one can frequently say: for physical reasons, the sign must be positive, and drop the negative or inversely. Mathematics is merely a shorthand method of recording physical intuition and physical reasoning, but it should not be a formalism leading from nowhere to nowhere, as it is likely to be made by one who does not realize its purpose as a tool.

L. A. Osborne: One may very easily assume a dogmatic attitude in giving expression to opinions upon the subjects treated of in to-night's papers. That is a state into which we are very prone to fall, and in the interest of real progress it is important that we should avoid it.

As engineers we are quite content to accept criticism from the layman of the structures which we build and plan, but when he attempts to tell us how to fashion our productions to accomplish the result which he requires, then we rise up and object. I feel this way about commenting on engineering education.

Some years ago I was persuaded to express my views upon this subject, which I did before this body, and I made up my mind never to venture upon such slippery ground again. The cries which went up from some of my academic friends led me to this renunciation, although there was an occasional friendly word which relieved the situation of utter hopelessness. That was several years ago. Now there is some satisfaction in knowing that some of the views expressed in my paper have since been adopted; and in a number of cases I have been accorded more credit than I deserved as the originator of some of the ideas there advanced.

I do not believe in telling the teachers how to do their work; I think we should better state what the finished work lacks. I am a product of the engineering educational methods in vogue fifteen or twenty years ago, and have long been what might be termed a purchasing agent for the consumer of the products which the schools turn out. I have thus been able to note certain tendencies, the resultant effects of which have left on my mind a sort of composite picture of the technical graduate as he has passed before my vision for the last ten years. While individuals may have qualities which set them apart from the crowd, still the average impress of the whole is that which produces the composite effect, the one which remains with me. Without presuming to point out how the quality can be improved, I recount here certain impressions which remain from my experience:

First, that 50 per cent. of the technical graduates that present themselves to be employed might better never have undertaken their profession; that at least that proportion of those with whom I have come in contact have apparently chosen an engineering profession more in the hope of the emoluments and not from any real interest in or love for the work.

How the real engineers can be detected in the first instance is a matter beyond me; but it is quite certain that a process of elimination which will put into the engineering classes men earnestly loving their chosen work, would not only make those men better fitted but would be a greater inspiration to the profession and a greater credit to their colleges.

Secondly, that of all those who remain, who may be termed good promising timber, the chief fault that I have to find with them, is that they are generally unable to grasp abstractions, that they are unable to generalize. Inasmuch as engineering *per se* is a profession dealing with specific problems, the tendency which follows application to its studies leaves the individual less able to treat with generalities. This is a question, therefore, of injecting into the courses something which will stimulate the powers of generalization which, broadly speaking, is more general culture.

Professor James has written very entertainingly in a recent magazine issue on the subject, " Of what use is a college education ", and the answer there given is the answer to apply here, but perhaps in a more restricted sense. Professor James contends that a person having the advantage of a collegiate training is better able to discriminate between the good and the bad in mankind. To the engineer, his training should give him that fine degree of discrimination which enables him to know what is good and bad in engineering, and inasmuch as engineering has become so important an adjunct to our everyday lives, the engineer should likewise have the discrimination to enable him to judge between the good and bad in mankind itself. We want men who know good jobs when they see them, whether the job is man-made or made by nature in the form of man himself. Engineers to-day are too self-centered; too bound up in the details of their profession. They are not as a rule men of the world but are men in the world with a too narrow perspective, largely due to the fact that their early training did not stimulate them in the right direction.

H. E. Clifford: There is at this time a very general agreement as to the advantages of a broad training for electrical engineering students, a training involving both breadth and depth. We do not want a training that is so broad, as to be superficial. We want a training which is well proportioned as to breadth and depth. It is interesting, I think, to note that a basis of science and cultural studies for engineering education was specifically stated by President Rogers, the founder of the Institute of Technology, in his application for the charter for that institution, and I distinctly recall the very strong emphasis which General Walker, during his presidential career with us, laid on these particular foundation stones of engineering training. There is, however, one danger, as it appears to me in this general agreement as to breadth of training, and that is the danger of the tendency to standardize education. It seems to me it would be a most serious drawback should this Institute or any body of men attempt to standardize educational methods. Education is not as yet more than an art, it is not an exact science; and standardization, while it may do for apparatus, certainly should not be applied to education.

The personal element has been emphasized in Dr. Steinmetz's paper. I think that is one of the highly important points to consider. A poor system may be made effective by a good teacher, and a good system can be ruined by a poor teacher. It is, after all, the personality of the teacher that accomplishes results. I may mention in this connection what has always appealed to me as a branch of research, as truly important as the research on inanimate things, namely, the research which the teacher certainly carries on in his investigation of a problem in teaching, as distinguished from a problem, it may be, in chemical or engineering investigation. There are many teachers, as there are many so-called research men, who are inadequately prepared for their work, who can carry out their teaching as research only under direction; in other words, they merely work along suggested lines but are not properly research teachers; but I do believe that research in teaching is an important branch of scientific investigation. After all, education has for its primary object the training of men to think straight, to think logically; and the particular type of education, whether it be civil engineering, or electrical engineering, or chemical engineering, is merely a medium for bringing that thing about, and that teaching of men to think logically can be frequently, and is undoubtedly frequently accomplished by training which is absolutely non-engineering in character. I think that is the reason why very often college men without any technical training whatsoever handle the larger problems of engineering more successfully and satisfactorily than some of our men highly trained from a technical point of view. This teaching of men to think straight, to think from cause to effect, must be carried out both in the class room and in the laboratory. No amount of training will help some men. Genius is not developed in a technical school unless there be some spark to begin with, and men without capacity, I believe, should be eliminated early.

I believe that many of our educational institutions are inclined to be too lenient in cutting out men who have no place whatever in engineering education, and I believe that a distinct step forward would be made if we should attempt to eliminate from the student body early in the course those men who convince us absolutely of their inability for the line of work which they have chosen. By eliminating these men, we should then have a class made up of men of exceptional ability and men of average ability. I would go further and suggest the segregation of the men of exceptional ability and the men of merely ordinary ability. I do not mean by this that I would put in the exceptional class the so-called—if I may use the college term—"greasy grind" type of man; but I mean the man who shows he has a broad outlook, keen intellect, real power—not the man who has intellectual facility which is quite apart from intellectual power. You may say, how are you going to tell such men? I believe that a good teacher can, to a great degree, discriminate between a man of merely ordinary ability, and a man of exceptional power; and I believe if this system were adopted that the results in producing men of the higher class of engineers would be very much superior to what exists to-day where men of moderate ability and men of superior ability are kept together and carried along in precisely the same way through a particular system of training. This would lead, also, I believe, to graduate work, a most important influence, and one which the technical schools have not begun to build up to the extent the importance of the subject demands.

Dr. Steinmetz also speaks of the importance of securing teachers from the open market. I believe that is also a very important point. The personal element is, after all, of paramount importance in teaching; and it seems to me absolutely essential that men should be secured and remuneration given which will enable these men to devote their time wholly to the problems of education. I do not mean that they are not to keep in contact with engineering progress; but there is great danger that a man who is trying to ride two horses will fall between the two. Teachers should keep in contact with engineering progress, but they should also devote their main interests to the educational side.

In regard to the matter of contact with engineering, some three or four years ago I gave considerable thought to this particular point, and it seemed to me it would be a very helpful thing if the interest, the knowledge, the breadth of view of consulting engineers could be brought into contact with the instructing staff of an engineering department. I suggested at that time to the authorities of the Institute of Technology the appointment of a committee of consulting engineers, and after due deliberation that committee was appointed. I believe that is going to be extremely helpful to us in bringing into the department the ability of men—just such men as Dr. Steinmetz refers to, men of force, men of standing in the engineering world, but who have the interest of the industrial rather than the teaching side of the subject first at heart.

In regard to thinking straight, I believe, as applied to the laboratory system, that every laboratory experiment should be made so far as possible a distinct engineering problem. It seems to me that the satisfaction which the students of to-day show in the *mere performance* of laboratory experiments is a very serious menace to the success of our laboratory system. Along these lines I suggested some three or four years ago a scheme of having every student in his laboratory work present a formal preliminary report of the scope of his investigation, the instruments needed, the particular scheme of operations, the results to be accomplished and their significance in the performance of the piece of apparatus being studied. This report is examined by some member of the instructing staff in consultation with the student before the work in the laboratory is performed, thus giving the opportunity for emphasizing fundamental principles and the advantage of personal contact of student with instructor. That is the system we are using at the Institute of Technology to-day and we find that it works infinitely better than the ordinary system of the mere perfunctory performance of laboratory experiments. There is one other point, and that is we must do something, I believe, to prevent undue collaboration in the student body. It is now very difficult to have a question concerning laboratory work take on even a semblance of newness after the work has been gone through with by a few sets of men.

A most important thing is to reduce the number of subjects taught in the curriculum. I heartily second what Dr. Steinmetz suggests on this point; and he has also suggested the difficulty in the institutions learning to do it themselves. Each institution fears if it reduces its curriculum it will be thought to be narrowing its training, instead of which it is broadening its training. There is too much fear that we may graduate a student who will meet something in his career outside of the institution, of which he has not heard or which will seem new to him. We must eliminate that feeling. Then too there is too much of the picture-book course. There are too many problems which involve merely the substitution of definite constants in definite formulas and do not require thought on the part of the students solving them.

If the function of this Institute is to advance engineering, and I believe it is, I think there is no better thing it can do than to study the engineering training in our colleges. I do not mean to study the engineering situation as ordinary men would study it, a mere cursory examination, the interviewing of a few instructors—they have as limited view points oftentimes as other people—but I believe this American Institute of Electrical Engineers might very well make a thoroughgoing investigation of our present methods of education, and I believe if they do that and then will make recommendations for the benefit of the technical schools, that will be something of even greater benefit than the standardizing of apparatus, or the preparing of a code of ethics or a code of engineering honor, and the influence of such an investigation will start on a more fundamental plane in the improving of engineering in this country.

F. B. Crocker: I agree with many of the remarks that have been made, including those of Professor Clifford and the points in Dr. Steinmetz's paper, also many of those in the paper by Mr. Scott. I must, however, take exception to one statement Mr. Scott makes in regard to the so-called concentric method. He says:

> This system clashes with time-honored educational ideas, but it presents arguments which are so rational that the existing method must assume the defensive.

I think that any radically new idea must always assume the defensive, and personally I think the older method could defend itself if necessary.

The proposed method in which the descriptive, the general, and the pictorial, precede the analytical, has several objectionable features. Even assuming that it is ideal as an abstract proposition, it has certainly practical educational difficulties which are fatal. It appeals to the mind, I think, because it is attractive to the student, and therefore to one who is considering the case of the student; but the result would be to make every one an electrical engineer. Mr. Osborne tells us that 50 per cent. of those who graduate should never have entered the institution. How many more enter the institution and fail to graduate? If 50 per cent. of those who graduated should never have done so, it is fair to say that 75 per cent. of those who enter the institution should never have entered. The proposed method would graduate almost all who entered, 75 per cent. of whom should not do so. Another practical objection that no one but an educator would see is this: when a man gets to the fourth year and has had no exacting subjects—in fact, I think the plan proposes that he shall not have any very serious subjects until the fourth year, which is reserved for them—the result would be that all would reach the fourth year, and what is to be done with them then? It is a serious matter as it is now, and would be much worse with the proposed plan. We cannot exert sufficient sifting upon them in one year to make sure that we eliminate those who should not graduate and enter the profession at all. I think that these are at least two serious if not fatal objections to any such plan.

In the first, second, and third years there should be some subjects so severe, so analytical, so eliminating as not to allow men to reach the fourth year who should not, and it is still more important not to allow men to graduate to the extent of 50 per cent., or even 10 per cent. who should not do so. This seems to me an important matter, about which any one having experience should give his views, so I state what I think quite frankly, but without any personal application.

H. W. Buck: The two essential elements of any form of technical education are the study of the theory and the study of the practice; in other words, of the mathematical side and the physical side. The study of the mathematical element brings forth the quantitative relation existing between the various forces, movements, and dimensions in a physical phenomenon. Under the department of "practice" is developed a general conception of the physical actions and also of their commercial relations.

It is frequently argued that a student should be carefully grounded in the theory before he undertakes any practical operation or handling of apparatus involving that theory. I believe that this is not in accordance with the workings of the majority of human minds. The study of thermodynamics, for instance, takes little hold of the mind of a man who has never personally handled a steam engine. The mathematical theory of an alternating-current transformer is merely a symbolic puzzle to one who has never had personal association with the current and voltage reactions in a transformer under practical working conditions. The theory of molecular combinations in chemistry is far clearer after a man has actually made such combinations experimentally himself, and so on through many instances.

The same point is illustrated in the history of the development of science and engineering. The experimental discovery of electromagnetic phenomena by Faraday came ahead of Maxwell's theoretical co-ordination thereof. The work of Watt came ahead of that of Carnot. Newton's famous apple was obliged to fall before Newton wove his mathematical theory of gravitation around the physical phenomenon so illustrated, and so on. It all goes to show that naturally in the development of engineering science, as well as in that of the individual mind, the physical action must be clearly pictured before the theoretical treatment can be intelligently pursued.

This sequence is not usually followed in technical education. It is considered orthodox to give a student a thorough theoretical groundwork before allowing him to handle machinery in which the theory is applied, and I am inclined to think that this sequence should be reversed. A clear mental picture should be first created in the mind of the student as a foundation for the theory. The criticism applies especially in the study of pure mathematics where equations, differentiations, integrations, and other operations are studied progressively, sometimes for four or five years purely *per se* without once introducing any practical applications of the performances. As a consequence the mind of the student becomes a maze of symbolic relations and a proper conception of what mathematics is for is lost.

The highly trained theorist who is apt to hold himself aloof from the purely practical man as belonging to a superior class, should not lose sight of the fact that theory is, after all, only a means to an end, the end being the practical application of natural laws for the benefit of man. The practical man who can apply the laws of nature usefully without knowledge of pure theory, is a more useful citizen than the theorist who can not apply his knowledge practically.

In order to obtain the best results in technical education, it would seem advisable for the student of engineering first to become thoroughly familiar through practical laboratory work with the tangible and visible workings of all the principal laws of nature involved in engineering, next to co-ordinate them by quantitative theoretical study of their relations, and finally to take up their commercial application in the study of the design of practical apparatus.

W. S. Franklin: Sir Philip Magnus, in a recent address before the British Association, said that in his opinion education can not be called a science until we begin to study the relations between methods of teaching and the final results accomplished thereby. It seems to me that teachers are, as a body, unable to approach the questions of education scientifically according to this idea, because the results of their work are to a great extent outside of the field of their observation. It is a consequence of this fact, I think, that teachers are especially prone to the elaboration of artificial and formal criteria for judging the results of what they are attempting to do in the class-room. The tendency of teachers to become increasingly formal in their methods and in the materials of their teaching is almost beyond control by the conditions of actual life.

Calling to mind Professor Clifford's statement that education is not an exact science, I wish to affirm the point of view of Sir Philip Magnus to the effect that at present education is not even an inexact science, and I believe that this movement on the part of the American Institute of Electrical Engineers, in which practising engineers and teachers join in the discussion of electrical engineering education, signalizes the beginnings of a scientific study of the subject. I think it is out of the question to expect the instructors in our technical schools to weigh the results of their work and to decide whether these results are what they are intended to be. In the institution with which I am connected, for example, we have some fifty or sixty teachers, and among that number there are four or five who have had engineering experience and who have a first hand knowledge of the demands which engineering education is intended to meet. Such a situation, which is common in all our technical schools, makes it impossible, it seems to me, to lift technical education to the plane of a science without the co-operation of engineers and teachers.

I agree entirely with Dr. Steinmetz in thinking that the hope of our technical education is in the narrowing down of our work so as to bring it within the reach of the student. I think that a great deal more stress should be laid upon the elementary sciences, physics and chemistry, and I believe that advanced technical subjects should be taught in such a way as to involve, again and again, a survey of the elementary mathematical and physical sciences which have gone before.

It would be a mistake, however, to curtail the time to be devoted to the first study of elementary physics and chemistry with the expectation that elementary knowledge could be supplied in the development of technical subjects later. The difficulty is that a technical subject, like steam engines, for example, is overloaded with detail; and a technical subject is never given with that accompaniment of simple illustrative lectures and simple laboratory work which is so necessary in the clearing up of the student's fundamental ideas.

Mr. Buck has expressed himself as to the importance of practical knowledge as a basis for theoretical study. I think I agree with Mr. Buck, although I prefer to use the expression "intimate knowledge" rather than "practical knowledge". I believe that the teaching of the physical sciences, reduced to its simplest terms, is *the transformation of intimate knowledge into general ideas*. If this be true, it is necessary to see that a young man has the intimate knowledge to begin with. For many years I have found that young men who come from the farm, or who have had experience in the shop, are very much better prepared for my work in elementary physics than young men who have been through a high school. If this kind of intimate knowledge is what Mr. Buck means by practice, I certainly agree with him, but I would hardly call it practice. The word practice, it seems to me, applies to the functions of an engineer, and what I call intimate knowledge is the knowledge a boy gets by connecting up an electric bell and playing with it until he is familiar with everything about it; or the knowledge a boy gets of hydraulics by building dams in brooks and by swimming and boating; or the knowledge a boy gets of mechanics by riding bicycles and jumping on rapidly moving cars and being nearly jerked in two. This is simple intimate knowledge of the kind that must exist before you can build up the theoretical structure which is called modern physics.

As to what Professor Crocker has said concerning the exacting character of the work in a technical school, I believe that we are now confronting a new situation in technical education. Twenty-five years ago, a man who wished to teach almost any branch of engineering had to reach up into the scientific world, as it were, and take hold of something from Rankine, or Weisbach, or Kelvin or Clausius, and drag it down into the view of his students. How otherwise could a man teach hydraulics twenty-five years ago? or dynamo theory? or the strength of materials? or the theory of the steam engine? Now, however, there is a great mass of simple technical literature exacting and precise. In the old days, mathematics was the only scientific study which could be made definite and exacting. Nowadays nearly every subject which is taught in the technical school can be made as exacting as mathematics, and, above all, the elementary sciences of physics and chemistry have been reduced to a basis which enables these sciences to be handled with an effectiveness which must soon entirely revolutionize technical education.

I believe that pure mathematics is tremendously over-emphasized at the present time in our technical schools. Every one, I think, admits that there is a very large percentage of useless developments in all of our mathematical text-books. A friend of mine, who knows his mathematics thoroughly and has no fear of it (for it is a kind of fear that holds most men in awe of mathematics), and who knows what mathematics means to the physical sciences, said to me several months ago that he believed that at least 30 per cent. of the subject-matter now included in our mathematical courses could be omitted without depriving the subject of a single element of utility for scientific and technical purposes. A mathematical friend of mine, one of the best teachers of mathematics of my acquaintance, has admitted the same in conversation with me. For my part, I believe that 30 per cent. of redundancy is a low estimate.

I think that over-emphasis on pure mathematics is to be found in nearly all of our technical schools, and I think that this over-emphasis involves not only the inclusion of a great many topics which are not useful in physical science, but I believe that it has resulted in a state of affairs which I may describe as follows: of all impersonal ideas the one most strongly imbedded in the human mind is the idea of number. Until the very recent developments of pure mathematics came about, a number always stood for some physical thing or things, beads or fish or dollars or cows, and the result is that *it is extremely easy to hoodwink a young man into the belief that he is studying about real things if his study involves arithmetic.*

I think that one of the most serious faults of our modern technical education is that it is overweighted with a great mass of numerical problems, the data of which are either entirely beyond the student's experience or with respect to the determination of which he is entirely ignorant. Such problems are, to my mind, utterly useless. They mislead young men, and also the teacher, into the belief that something is being accomplished, whereas nothing is being accomplished at all.

To my mind, nothing is more important than to associate physical ideas with mathematical operations and formulas in the work of teaching. In my class-room I have often used the following illustration: consider a wage of $2.00 per day; if you multiply this wage by 10 days you get $20.00. Now I ask my class, "how do you multiply $2.00 per day by 10 days?" but they never seem to have any notion behond the writing of a simple tabular arrangement on the blackboard. I say, "No; you have got to work 10 days at $2.00 per day in order to multiply $2.00 per day by 10 days and get $20.00". The 10 days of labor is the physical operation that lies behind the mathematical operation, and there is scarcely a single mathematical operation in the whole range of physical science which does not have as definite a physical significance as this operation of multiplying $2:00 per day by 10 days.

L. B. Stillwell: The answer to the question, "to what extent should the technical school devote attention to purely professional subjects"? depends upon the relative value to the graduate of professional information as contrasted with education. Undoubtedly professional information may be imparted in such a manner as to educate, but for the purpose of expressing an opinion it is, perhaps, sufficiently exact to speak of "education" and "information" not as they are inter-related but as they are contrasted. Before the question can be answered, however, it is necessary, as Mr. Scott has suggested, to define one's idea of the part which the engineer should be prepared to take in modern life.

As regards this, the conception which apparently is widely accepted, not only by preparatory and undergraduate technical students but also by many "over-practical" parents is narrow and short-sighted. The enormous advances in physical science, and in the application of physical science to modern life, are glibly asserted and reiterated, and the effects of utilization of natural laws and forces upon the economic and social structure of society are more or less appreciated. But in educating a boy for the special purpose of taking an active part in this gigantic movement, the tendency too often is to start him at the earliest possible moment in a narrow channel of thought, to narrow his intellectual horizon and make him a mere mental mechanic. This, in my opinion, is all wrong.

If graduates in engineering courses are to become generals, or even colonels, in the army of engineers it is obvious that the breadth of their training should bear some relation to the fundamental possibilities and demands of the field in which they are to labor. The engineer who desires to rise, therefore, should start, if possible, with a broad education. Truth is truth, fallacy is fallacy, and logic is logic, in any field of thought. In nine cases out of ten, mere professional information acquired in the technical school is of comparatively little value to the graduate. This is particularly true in the case of a rapidly advancing art such as electrical engineering, for the reason that a considerable part of the professional information acquired in school is out of date by the time the graduate attains a position where he has opportunity to utilize it. Practical information which he can really utilize is acquired rapidly in factory or office, in mine, mill, or laboratory. Following graduation, the work which young engineers in almost all cases are called upon to do for a number of years is highly specialized and professional information comes to him in the most effective manner. During these years, if he is working earnestly for advancement, his field of observation and thought, so far as his professional work is concerned, is necessarily limited and comparatively narrow. The opportunity for fundamental education rarely presents itself after completion of the course in the technical school, and unless prior to that time a broad foundation has been laid it never can be laid.

The ideal education of the engineer who hopes to be more than a private in the ranks is a broad one. It cannot very well be too broad. In my judgment, whenever possible, a technical course leading to a degree in engineering should follow a four years' course leading to the degree of bachelor of arts or bachelor of science. In other words, engineering courses should be regarded as professional courses and should perform the same function in the education of the engineer that the law school fulfils in equipping a graduate in the course of arts for the practice of the law.

In those cases where this is not possible, and the student finds himself necessarily limited to a course of four years in a technical school, the aim should be decidedly to educate him rather than to train him.

In my experience the following facts of observation have impressed themselves upon me:

1. American engineers to-day do not hold positions of leadership in the community to an extent commensurate with the part which engineering plays in modern life.
2. The graduates of our technical schools, while averaging well in respect of mental ability and earnestness, often lack mental perspective and are rarely capable of expressing themselves with accuracy and force.
3. The men who rise highest in the engineering profession, generally speaking, are the men of broader education.
4. Chief engineers and managers have little trouble in finding draftsmen, and less in finding competent calculators, but the demand for "all around men" always exceeds the supply.
5. The higher executive positions in administration of our great railway and industrial corporations are held rarely by engineers. In recent years undoubtedly the engineer has been making substantial progress in this direction, but usually he fails to occupy his share of the higher places in administration.

So much for personal impressions based upon observation of results. As to methods, I cannot presume to offer advice to the teaching profession. It would appear obvious, as Mr. Scott says:

> That details of method are to be determined by varying conditions and are to be adapted to the vaiying personal qualities of the young men.

I would particularly endorse what Mr. Steinmetz has so ably said in regard to that fault of teaching which aims at quantity and not quality. There is no good reason to believe that the ability of the human race to acquire and digest knowledge has increased abnormally during the last decade or two, but comparison of requirements in colleges and preparatory schools to-day compared with the curricula of 20 years ago, indicates that our educators are proceeding upon the theory that the average student of given age to-day is endowed with mental capacity greatly exceeding that of his father, not to mention his grandfather. The result in a great majority of cases is mental indigestion from which the student sometimes, but not always recovers, after graduation.

The cause underlying this unfortunate and very serious state of affairs is to be found probably in the ill-advised competition of schools and colleges. The school of the future is the school which will have the courage to cut out of its curriculum 25 per cent. of the studies now required for graduation and will emphasize not quantity, but quality.

Albert F. Ganz: Dr. Steinmetz says that:

> The least that can be expected from the college is that at the time of graduation, the student still knows all that he has been taught during his college years. To accomplish this, it is necessary to keep up the study of every subject to the end of the college course.

This seems impracticable. How are we to cut out some subjects and have less quantity, but yet to keep up every subject throughout the whole college course? I expect Dr. Steinmetz does not mean this to be taken literally. For instance, I do not suppose he thinks that the subject of chemistry should be taught to the end of the college course.

Chas. P. Steinmetz: I do.

Albert F. Ganz: Then I should very much like to know how we can cut down the course and yet keep up the study of every subject throughout the four years?

I have read Professor Karapetoff's paper carefully, and while the method has many good points, I feel very strongly that the college is the place where theory must primarily be taught; and that this theory must be supplemented by illustrations from practice by means of descriptive lectures and laboratory work.

I believe that there are four objects to be accomplished by a technical education: first, training of the mind so that it becomes an efficient machine; secondly, storing in the mind fundamental principles and facts to give to the student an understanding and a perspective of his profession; thirdly, an acquaintance with the sources of information so that the student may know where to find information; and fourthly, general culture. It seems to me that in the college we should aim to teach those things which the engineer must know, and which he cannot readily obtain in practice, nor from general reading. As an example, the mathematical theory of alternating currents should be taught in the school, because in practice the engineer would not learn that theory nor would he readily be able to get this from his own reading. I also believe that the laboratory experiments should be designed so as primarily to impress upon the students the main fundamental principles, not designed to imitate the tests that have to be performed on the test floor of a large manufacturing establishment. I do not believe that the latter is possible in a college laboratory. That is an example of the kind of information which the engineer can get from practice. I always advise our graduating students to spend one or two years after graduation in the shops of one of the manufacturing companies. Fortunately for the technical schools, the large electrical companies have established apprenticeship courses where it is possible for the student, after graduation, to become familiar with large machines under commercial conditions.

I should like to have the Educational Committee suggest what cultural subjects should be included in the curriculum, and how much time should be devoted to them. At the Stevens Institute we include in our curriculum courses in business engineering, English, German, and some lectures on patent law and on contract law, and we hope to include more cultural subjects.

Mr. Buck speaks of teaching the design of practical apparatus. I question whether in a technical school it is possible to teach practical design to any considerable extent. I rather agree with Dr. Steinmetz, that it is better to analyze existing apparatus than to attempt to make actual designs.

J. G. White: There seems to be a virtual unanimity of opinion, that the aim of the college education for engineers should be to build up a foundation or groundwork based on the fundamental subjects of which the engineer should have knowledge, rather than to give him specific information. I fully agree as to the thorough wisdom of this. Specific information can be readily acquired after leaving college, whether it be with one of the large electrical companies, or in a consulting engineer's office, or out in the field in erecting machinery, or elsewhere. The fundamentals, such as a good general knowledge of mathematics, and a thorough knowledge of physics and chemistry, both of which I consider extremely important, cannot readily be acquired in the field; that is one of the reasons why they should be acquired during the college courses. The subjects that are useful primarily because they are a benefit to one's general culture are less readily acquired in practice, partly because the facilities are not so conveniently at hand and partly because one is likely to be absorbed in the performance of daily routine duties, so that it is difficult to find opportunity to put thorough study on subjects not requiring attention by reason of such routine duty.

So far as the general usefulness of different subjects is concerned, it seems to me that, as intimated in the previous statement, there should be a thorough and broad training in mathematics, in chemistry, and in physics, and I believe with Mr. Steinmetz that all three of these can be carried through the college course. No one should specifically study calculus during the entire course, nor specifically study elementary chemistry during the entire course; but in the later studies, dynamo design, for example, enough calculus can be used advantageously to keep one from forgetting the general principles of calculus, and so one can, in the study of electrochemistry, in connection with experiments with storage batteries, or in other like ways, have enough use for chemistry to prevent one forgetting the elementary chemistry learned in the freshman year. In similar ways, if a course is laid out correctly, one can be kept from forgetting other subjects which have gone before. In addition to English, which I am glad to see is being followed up more consistently and persistently, one of the subjects which I perhaps am inclined unduly to value is the study of Spanish as compared with other language studies. It seems to me that Spanish has practically as much educational value, and almost as much value as a culture subject, though perhaps not quite so much as French or German; but it is so much more likely to be of use in practical life after graduation, that I strongly favor the average engineering student studying Spanish, if he possibly has the opportunity of doing so. If he can study one other language, Spanish as a second is distinctly desirable. It is a comparatively easy language to learn.

Another suggestion which perhaps our friend from Stevens may like to hear in plain English is that ordinarily I believe the college professor is too much inclined to rely on lectures and too little inclined to depend on well-worked out, well-planned text-books which some other professors, or groups of professors, have written. The lecture room is of great value in physics, chemistry, and in electrical engineering, for illuminating and illustrating fundamental principles, but these fundamental principles should be put before the student in such shape that he has something to study and restudy, can have impressed on his memory. His time should not be wasted by making a lot of notes and going through the mechanical operation of copying them, when, after he has them copied, he probably has no adequate understanding of the subject. Another beneficial trend of many general educational courses is toward doing away with too great freedom in elective studies. About the time I left college there seemed to be a great tendency toward putting all students entirely on the elective system, leaving nothing on the required curriculum. There seems to be a drifting back to the good old-fashioned days of mapping out a set course for young men, and I think that practice can be advantageously followed further than it has been. It seems to me that a group of professors in consultation with other officers of an educational institution, and with the advice of graduates and trustees, can decide to better advantage what the ordinary engineering student of 17 or 18 years of age should study, than can the young man himself. That is surely true of technical courses, and I should be glad to see more text-books, fewer elective studies, and the required studies more confined to general principles and foundation work and less given to doling out general information.

W. E. S. Temple: There is a noticeable tendency on the part of those who have been out of school for ten or twenty years to overestimate the amount of preparation which the technical graduate should have. In considering the subject, it is necessary to try to state what the object of an engineering education is; we can then see better what it should consist of. It is admittedly impossible for a man still in school to know just what line of work he may be best suited for, yet this is the age of specialists in electrical engineering, as well as in other professions and on this account the object of the technical training should be to provide the man with the means to receive the best development in that special kind of work into which he may be placed after graduation.

The education must therefor consist in grounding the man in principles and general applications. This will give him the tools with which to develop himself when he becomes enrolled in the school of experience. A great many rules and formulas have been suggested, indicating how best to accomplish the laying of this general foundation for development, but rules and formulas cannot be applied here any more than they can be to regulating the politics of New York or of Philadelphia. We must set before ourselves a certain aim, and keep examining ourselves as to methods, taking account of stock as it were, and make sure that we are getting the best results possible.

Another thing that should be accomplished in addition to getting a thorough foundation in technical principles, is lifting the man's ideals high as to his future position as a man of affairs. There is no reason in the world why the engineer, who is responsible for so large a proportion of the wealth and resources of this country, should not have more control over them, and more profit from them.

The quality of the work done by a student actually depends upon himself as much as it does upon his teachers, and therefore the entrance requirements deserve as much attention as does the laying out of the work after he begins his technical training. To outline the actual subjects which should be taught is not difficult. There are a number of lists which are in use, some preferable to others, but all of them good, for they are producing favorable results. It seems to me there should be more of those subjects which develop the man's power to reason along lines related to engineering, and less of those which fill his mind with a useless store of technical data that can be found in handbooks. As to the suggestion in Dr. Steinmetz' paper that physiography, metereology etc., be taught; why not a course in architecture and perhaps practical politics too? These are really as much related to the subject of engineering, and are as broadening, as the subjects he refers to, perhaps more broadening. It seems to me that specializing is not preparing the student for the best development, and a too great indulgence in it prevents the college from doing the greatest good for its men. I am referring, of course, to the undergraduate students.

One of the vital features in the education of the engineering student, it seems to me, is the method followed in taking up the work. Mr. White referred to the matter of lectures; I do not think that any hard and fast rule can be laid down for this. The rapid progress now being made in electrical engineering demands that some of the subjects relating to the applications of electricity be taken up in lectures, I know of no text-books in existence at present which are suitable for this part of the work. The elementary subjects, and the general applications of electricity should, in my opinion, be invariably taught by the use of carefully selected text-books, concurrent with the solution, by the student, of various kinds of engineering problems. These problems should involve not only the new ideas and principles as they are taken up, but they should also depend upon subjects already gone over in earlier parts of the course.

The classes should be subdivided in sections of about ten men each for all recitation work, thereby insuring more nearly individual instruction, and making it possible for each man's needs to receive attention. The greatest stress should be laid upon promptness and accuracy and general attention to work. The student should be penalized for absence from classes, or for tardiness in doing the work assigned to him, even though he may do that work in a most satisfactory manner from every other standpoint.

Laboratory work should be individual as far as possible. If the men work in groups of two or three or more, upon one test, it is not possible to make sure that all of them get all the benefit which they should have from the work. The inferior man will allow the better man to do it all, nearly every time. The only sure cure for this is to make each man work alone. This method is, no doubt, more expensive; but if the thing is worth doing at all, it is worth doing well. Furthermore, the best results will be obtained if each man is obliged to set up his own apparatus, and wire up his own test. If he is a particularly good man, it is not a bad idea, occasionally, to put the machine in trouble in some way or other; this method will require more time for each test, but quantity is not what we are aiming at; it is quality we are after, and this method is bound to produce a far higher grade of work, and to develop in a much greater degree, the man's thinking, and reasoning powers.

The method of concentric instruction has been very adversely criticised, and it seems scarcely necessary to speak of it any further. The idea, if applied to one subdivision of one of the subjects of electrical engineering, might be good. It is however utterly impossible, as has already been pointed out, to go into details of construction and operation of machinery, particularly electrical machinery, without having the theory to resort to for explaining the why and wherefore. As I understand it, this method proposes to complete all the practical considerations first, leaving the theoretical features until last. The result of this would be that in going over the practical parts with no theoretical preparation the man would perforce become a confirmed empiricist, and when he came to the theory later on, he would be perfectly satisfied to omit it entirely, or at least he would fail to give it the proper attention. The summary of the paper shows a great many things which this concentric method will accomplish; it will produce a somewhat finished artisan at the end of the first year, a little better artisan at the end of the second year, etc. It reminds me of a machine, that will do a dozen different things, but none of them properly.

Louis A. Ferguson: The great value of an engineering education to a young man about to start in his life's work lies not so much in the actual knowledge he may bring with him, but in the training which he has received. The accumulation of a mass of data is not the important thing, but the reasoning power which he has acquired is what will serve him in good stead in after life. The technical training of our engineering schools develops an analytical turn of mind and teaches the young man to differentiate between right and wrong, promotes sound judgment, which, after all, with initiative and optimism, is one of the great factors in producing the successful man in any walk of life.

It is a mistake, as Dr. Steinmetz has clearly pointed out, to try to jam the maximum amount of information into the student in one year, only to be forgotten the next. Premium should be placed upon the development of reasoning power rather than the mere memory of the student, and any subjects that he must know in his practice after graduation should be kept constantly before him throughout the entire course, so that he may carry his knowledge, once acquired, with him into the world.

There is a tendency in some educational institutions to a practice which I think is not conducive to the best results. I refer to what might be called "inbreeding", that is, the general employment of graduates of a given technical college as teachers and professors in that college. This promotes narrowness of view among the students, mental fatigue among the teachers, resulting in the decline of the educative ability of the institution. The faculty of an engineering college should be made up of men graduated from as wide a range of colleges as possible. Eastern colleges should have some professors who have been trained in the West and South, and western colleges should have professors who have been trained in eastern institutions, so as to give as broad a character to the education as possible, and to keep alive in the faculty itself real interest in its work.

We find in the management of industrial corporations that the best results are obtained by following this principle in the employment of engineers. The very college patriotism which exists in the heart of every true American will prompt him to try to equal in efficiency his fellow engineer from another institution, and this rivalry, which must be friendly to accomplish the desired result, is bound to make finally for the interest of the corporation.

Professors and teachers are not as a rule sufficiently encouraged by their college management to come in contact with the practical side of engineering, or the work accomplished in other similar institutions, as they might be were they given the opportunity to mingle more with practising engineers and industrial managers and by travel in this and other countries. They are, as a rule, forced to gather their information by reading and study which is less satisfactory than actual contact and observation.

Why, if the industrial corporations find it profitable to send their engineers and managers to other parts of this country and Europe to study conditions and make comparisons, should not the technical colleges and institutions find it equally so to do the same with their teaching staff?

The scope of the course of electrical engineering in some institutions, it seems to me, is too narrow. The graduate electrical engineer, for some reason, is considered by some employers to be devoid of ability to discuss anything but electricity, and his opinion on other matters is discounted and oftentimes very unfairly to him. This is unfortunate, as there is probably no branch of engineering which requires so general a knowledge to be successful as that of electrical engineering.

The course in electrical engineering should include the fundamental principles of mechanical engineering, and civil engineering, chemistry and hydraulics, building construction and general business law, as well as theoretical and applied electricity. The student should be impressed with the fact that a general fundamental knowledge of the branches of engineering other than pure electrical is paramount to ultimate success in electrical engineering, if by that we mean obtaining a position whereby one is given the responsibility of conducting large engineering undertakings, or the management of large industrial operations.

Samuel Sheldon: That educational institutions are unable to obtain the best type of instructors because of the low compensation which they offer is recognized by professors, by those who wish to be professors, by engineers, and by the presidents and trustees of these institutions. The mere announcement of the fact will not better the conditions. Much could be accomplished by a co-ordinated movement on the part of all technical institutions to increase the tuitions from students who are able to pay, leaving the funds which are derived from philanthropists to be distributed, so far as they last, in defraying the expenses of worthy and selected students. In reference to quality, as distinguished from quantity, the Educational Committee of the Institute would perform a useful service if it should bring about a curtailment of the matter which is at present presented in connection with the instruction in each and every subject.

in existing courses. Such curtailment, in view of the fact that courses will doubtless be limited to four years for some time to come, would result in a saving of time which could be utilized for needed culture subjects, and for the amelioration of existing conditions towards which the so-called concentric method of education is directed.

In reference to Mr. Scott's paper, the extracts from the Institute papers are on the whole so general as to be of little value to one engaged in laying out a curriculum. One, however, and that is from the paper presented by Professor Karapetoff, is very definite, and the original is accompanied by a specific schedule for each year. The advantages which it is claimed would result from the use of this concentric method should be obtained, if possible, but it does not seem necessary to make use of such radical means as are outlined in that schedule. Associated with it are two marked disadvantages: first, the hiatus in the pursuit of mathematical studies must inevitably result in educational inefficiency; secondly, training in physics, which is an absolutely essential prerequisite for any serious engineering study, is deferred to too late a period.

Tests of the absorption power of an average freshman indicate that a cyclopedic view of all engineering could be profitably given during the freshman year without consuming more time than could be obtained from a judicious curtailment of the freshman schedule, as at present existing in most institutions. Experimental electrical engineering is also required early in the concentric schedule. Physical laboratory work could readily be so laid out as to constitute a course in experimental electrical engineering.

P. H. Thomas: In its broadest sense, engineering is a method, not a profession. By this view, " engineering " is the application to new problems, through the methods of logic, such as mathematics, the knowledge of experiment, and experience. This method is applicable to many branches of activity not included in a narrow definition of engineering. There is every reason why the banking, trading, and selling work of the country should be carried on by men trained as are mechanical, electrical, or civil engineers, but in a different subject-matter. In fact, this state of affairs seems to be rapidly approaching.

Although the object of technical education must be strictly speaking, to perfect a man as an engineer, expediency requires that at the same time he must receive such culture training as he is to get at all during the same period. The man should by no means be sacrificed to the engineer. Fortunately, such culture training as is appropriate will usually benefit the engineer. The factors of greatest importance underlying successful engineering are perhaps the following:

1. A thorough appreciative knowledge of the laws of nature and of the properties of materials. These laws and properties, as used in engineering, are simple and relatively few.

2. Familiarity with the mathematical and other logical processes by which the fundamental laws are to be applied to special cases and results numerically computed. Here self-confidence and the power of applying knowledge are of the greatest importance. It is here that many graduates are lacking. This section must be construed very broadly to include the underlying principles of all types of machines.

3. Familiarity with the results of experience; what has actually been accomplished in the past and just how. This is of the greatest importance and is, further, the basis of the great mass of actual engineering work done. The results of past work are found partly in the general parctices of the community, partly in books and periodicals, and partly in the records of individuals of experience. Here should be included, at least for the more ambitious engineers, a knowledge of the more important experimental work done and the new methods and apparatus proposed by inventors.

4. Acquaintance with the actual methods, standards, practices and engineering terms in vogue in any particular community. These may be different in different places; but one engineer can not work with another without this acquaintance.

Over and above these four conditions the effectiveness of an engineer depends, of course, on his personality, but this is not properly a matter of education.

The actual period of an engineer's development in which he may be said to be receiving his education is perhaps ten to fifteen years, beginning with his technical school work. Of this period, four years are usually devoted to school work, a good proportion. Here comes the practical question to be considered: to what shall these four years be devoted? In my opinion to the first and second and to the more fundamental facts in the third division of engineering knowledge just given, and as well to some culture studies.

The study of natural laws, of the characteristics of materials and all mathematical work is best done in class work. Here should be included the laws of force and motion, of heat and sound and electricity; such subjects as mechanism and mechanics and thermodynamics. Also, for electrical engineers, such information as the laws of parallel circuits, induction, resonance, wave motion, the natural characteristics of different types of electrical apparatus intrinsically, as transformers, series and shunt motors; also principles of compounding, field distortion, etc., induction motors, synchronous machines, etc. But not such subjects as commercial designs or designing of apparatus, constants of design, the relative merits of different makes, physical description, compilations of actual costs, efficiencies, and other data of actual plants, nor much study of actual installations. These all tend to distract and to lessen interest in the more fundamental things that cannot be learned later.

The subject-matter here assigned to the school years is in the long run of the greatest importance and cannot be well gotten later. The other subject-matter covered in the four divisions of engineering knowledge are readily acquired in actual practical work, but only with the greatest difficulty in the class room, and then imperfectly.

The engineer must specialize, even within the divisions of civil, mechanical, electrical, etc. The specialization should not however prevent an appreciative knowledge of all other important branches. As Dr. Steinmetz has said a good descriptive short course can give a group of fundamental phenomena, and the essential or individual character of such a branch in a way, that will permit a real appreciation of its significance. The influence of these related branch studies is tremendously broadening.

It is not for the practising engineer to specify in detail the course of the technical school, this is for the specialist in education, the professor; but the engineer may suggest a measure, by which a course may be judged, the following is an example. Does the course give:

1. A clear, thorough, appreciative knowledge of the natural laws used in engineering work. Also, a good knowledge of the properties of materials.

2. A clear, working knowledge of the mathematical methods, formulas and other logical processes by which the fundamental laws can be applied to individual cases and numerical computation made. Also, a familiarity with the characteristics of the sorts of apparatus commonly used (not commercial types). In electrical work treat the motors, generators, students. Is the knowledge and training of such a character that he can personally use his data and formulas and have confidence that he is right?

3. Has the graduate enough general culture to feel the equal of and at home with the other men (not necessarily engineers) that he meets?

4. Has the matter been so presented as to be grasped in the easiest and most permanent manner? Has the interest been kept up and the meaning of the work made clear by some view of the practical field into which the student is to pass?

W. L. Robb: A matter that has an important bearing on the curriculum of engineering schools, but not mentioned this evening, is the relative lack of preparation of men who enter these schools. It is a notorious fact that the great majority of men who enter technical schools have not completed a high-school course. Men generally enter the technical schools at least a year before graduation from the high schools. Virtually all of technical schools have lower entrance requirements than the colleges. Where the requirements are nominally high, the examination in the non-mathematical subjects is relatively easy, the examination in mathematics being the real basis of entrance. The majority of men entering medical and law schools at the present time are college graduates, much more highly trained than the men who enter the technical schools. As a result, a large part of the first two years in the technical schools has to be given, not strictly to engineering subjects but to general mental training. Under the present condition of things, culture subjects have a place in a technical school, but I believe they only have a transient place. I do not think that a course in English or history or political economy has any more place in a technical school than in a medical or a law school. We should see that the entrance requirements of the technical schools are brought up at least to the entrance requirements of the colleges.

With entrance conditions as they are at present, the first two years of a course should be mainly given up to the study of mathematics, chemistry, physics, English, and one other language, preferably a language that is inflected. I do not think it makes much difference whether the language is Spanish, French, German, Latin, or Greek. As far as the commercial usefulness of the language is concerned, I believe thirty days spent in a foreign country will prove more valuable than two years' study of the language in a school.

The third year of the course should be devoted to mechanics and the fundamental principles of civil, electrical, and mechanical (including steam) engineering. There should not be much, if any, difference in the way these subjects are taught in the various engineering courses.

The fourth year I would devote mainly to highly specialized subjects in that branch of engineering in which the student elected to take his degree. The student should have the privilege of specializing along some desired line before graduation.

I do not think we should have in engineering schools courses specially devoted to business methods, depreciation, operating costs, and similar subjects; but I think any man capable of being at the head of an engineering department should infuse these subjects into the minds of his students in connection with the regular work.

C. O. Mailloux: I have, presumably, at the present time, all of the qualifications for speaking on this subject, since I am a practising engineer, and, at the same time, happen to be an "amateur" teacher in one university, and an "amateur" student in another. The complete period of instruction of an engineer, which Mr. Thomas speaks of as being fifteen years, is too short for the man who believes in progress. I find that it can be profitably extended to at least twice that time.

I agree fully with Mr. Stillwell. His discussion states the facts, from the standpoint of the enlightened progressive engineer, very well indeed. I endorse his plea for broader education, now, just as I did at the Great Barrington meeting. Like him, I have found, and I so stated at Great Barrington, that, oftentimes, the man of broad general culture is of greater utility, and makes more rapid progress, than the man who specializes too soon. I also agree, with him, that there is an abundant supply of the mediocre man, but a scarcity of the man able to do original work. In looking for the causes, we find that there are many, and in looking for the remedies, we find that they are diverse. Yet, after all, we find that the general principles have already been reviewed in previous discussions; and I noted, with some interest, as the discussion progressed, and as I classified the points covered, that most of the formulated statements regarding the requirements of technical education have been given already, in previous discussions before the Institute, particularly in the papers of Professor Esty and of Dr. Sheldon. Professor Esty gave, in his paper, a resume of the requirements, so well, that, even after the discussion here tonight, we do not find that we can improve much upon them. Dr. Sheldon's discussion differs from Professor Esty's only in so far as it goes further, or attempts more. It aims to build a "pyramid of knowledge" of greater height, and therefore postulates a broader base. I have already spoken of that pyramid fully, in my discussion, at the Great Barrington meeting; and I need only to add now that my views have not changed in regard to it. In that discussion, you will also find a reference to the subject of "mathematical dyspepsia" which, I think, is still pertinent. There is nothing which causes so much contention and dissatisfaction among teachers, students, and engineers, as the teaching of mathematics. A great deal of effort has been devoted to finding better methods of teaching mathematics. I am often questioned by both teachers and students of engineering about that subject. I expressed my views fully on that subject at the Great Barrington meeting. I also made some reference to the views of Dr. John Perry, who has some perhaps radical, but very good, ideas on the subject. I am glad to say now, that the ideas of Dr. Perry have actually led, since then, to wholesome reforms in methods of teaching mathematics in England.

My own view about engineering education is that we should attempt much less, and yet, attempt much more. We should attempt less in not trying to cover so much ground and so many details, but we should attempt more in trying to cover fundamental ideas and principles more thoroughly. I often find that students are bewildered and discouraged by the size of the text-books given them. If the text-books were smaller, or less terse or rigorous; if they covered fewer points and covered them more thoroughly, they might, perhaps, be less imposing, but they would be more "effective", as repertoires of knowledge for engineering students who do not expect to become teachers.

On the subject of lectures, as distinguished from text-books, I may say that my experience, both as a teacher and as a student, leads me to believe that the ideal method is to combine the best *features* of both. I believe in a method in which the student receives guidance and instruction primarily, and whenever possible, from lectures, but works in connection with text-books, or, in the absence of text-books, (and, *preferably*, in all cases, when it can be done), with a carefully prepared up-to-date, and not too much condensed, syllabus. My own method in teaching, is to ask the student to take as few notes as possible. I try to give them ample ready-made notes of all the principal points and all the main details of the discussion; and I also refer them to all books which can be of assistance to them by throwing more light on the subject. I know, by personal experience, how often one makes errors in taking down notes and how difficult it is to correct notes taken down wrongly.

In regard to the teaching of mathematics, pure and applied, there is danger that, while trying to cover the moderate wants of one class of men, we may neglect to cover the higher wants and aspirations of another class. We must consider the kind of material that we work with, and the kind of men that we expect to turn out. It all depends on how high the pyramid of knowledge is to be built. If we seek merely to turn out mediocre or average men, we can get along with relatively little training; but if we wish to turn out men who are to be colonels or brigadier generals in the profession, then we must place at their disposal the facilities whereby they may acquire that higher training which they should have. It may be that we cannot do both of these things in the same class, or even in the same school. At this point let us say a word about the distinction between theory and practice. I think that too much emphasis is laid upon the importance of the student being brought into physical contact with those facts which he can gather with his eyes and hands. Any person who has given the slightest thought to education knows that it is not so much the facts which are discovered by the eyes and hands that are important, as it is those which are discovered by the mind. There are certain " facts " which are more important than even the individual, oftentimes detached, physical facts, gathered by the hand or the eye; and those higher facts are called principles. These are usually the facts which furnish the key to whole treasures of facts. Thus, while it is true, as Mr. Buck said, that Watt came before Carnot, yet, it is also true, that Carnot came before Corliss. We also know that Hertz came before Marconi, just as Maxwell and Faraday came before Hertz. There is an important distinction to be made between the use of mathematics as a means of technical training and as a means of technical research. There is a legitimate use for both. We may possibly have done too much in the way of using mathematics purely as a means of training, for engineering students. We should, in the training of engineers, perhaps, use more applied mathematics and less pure mathematics. But here, again, we should bear in mind the needs of the higher technical science and look to the great engineers to see what they have done as the result of specializing and higher training. The distinction of a school is due partly to the distinction attained by the great men who received their training at that school, and partly to the distinction of its teachers. It is worth while and is inspiring to look at some of the great achievements in our profession, and to see the means whereby they have been attained. Some of these things are of the greatest significance, and they point to a moral in regard to methods of teaching and the way it should be directed. Two of the greatest achievements in electrical engineering, in my opinion, have resulted from the solution of differential equations. They are feats of applied mathematics. The first of these achievements was made when that great electrical engineer, Lord Kelvin, solved the differential equation since known as the "telegrapher's equation", and, in doing so, predicted all that it was essential for us to know, and foretold the facts and the practical essential conditions that were afterwards observed, in regard to submarine telegraphy. That solution was the key to submarine telegraphy. The second achievement was another solution, a far more complete solution, of that same differential equation, by Dr. Pupin; and this latter solution, which turned out to be the first general solution, has done almost as much for telephony, as the solution of Lord Kelvin had done previously for telegraphy. These two cases show that, when the greatest results in electrical engineering are the goal, even the most complete equipment, intellectual or technical, is not too great. As to what constitutes the modicum of requirements which a student of engineering should satisfy, my opinion is that these requirements include three or four principal branches. I might say that, of physics—the fundamental physics of energy in all its forms and manifestations—the student cannot have too much. He might have too much physics if he is led into the by-paths of physical research too early, but of fundamental physics he cannot have too much. If we include mechanics and chemistry in physics, then we may say that the principal part of the engineer's education should be physics. Let us say, then, physics, mechanics, and chemistry; and let us not forget mathematics; but there should not be so much pure mathematics as applied mathematics; there should be just enough pure mathematics to enable the student to get along in applied mathematics. I believe strongly in analytical mechanics and even in some mathematical physics, both of which are applied mathematics, with physics. In a word, I believe in plenty of fundamental physics, taught both ways, experimentally, and also by mathematical methods. Too much time is spent in teaching mathematical abstractions which the students cannot possibly remember. The pure mathematics should include the essentials and fundamentals, of algebra, geometry, trigonometry, and the calculus, leaving the refinements thereof for later attention on the part of the student, after he has learned to appreciate their value. I cannot quite agree with Professor Robb as to the transient features of culture in the curriculum. He contradicts that opinion himself, to some extent, when he says that facilities should be given to students for specializing, since specializing is a means of broadening the student's culture. One of the sad facts which should be realized more than it is, is the want of general culture in the engineering profession. Mr. Stillwell has brought that out clearly. I believe, with Professor Robb, that one of the most important difficulties lies in the fact that the students are placed in contact with the engineering part of their education too early, before they have had the necessary amount of preparation, or even, I might say, of intellectual growth and development. Perhaps the solution of the entire problem will be to increase the requirements in regard to the preparatory studies pursued and to apply an inferior limit to the age at which students are allowed to enter the polytechnical courses. We should not expect to make children engineers, any more than to make them doctors or lawyers. One remark of practical importance is that made by Professor Clifford, in reference to a committee of engineers acting in consultation with the faculty or the heads of the departments. There may be a great deal of good there; but there is also a possibility of harm. I know, from having seen men teach, that there is as much difference in teachers as there is in pupils and I know also, from having attended lectures by " outside " men, so-called, that some of these lectures are apt to be quite as bad as they are apt to be good. I mean that the practical man is " fit " as a teacher only when he has retained such contact with the theoretical side of his profession that he can still be able to lead instead of mislead the student, when he presents his subject to them. I have seen cases of that " misleading " kind which brought home to me the lesson that he who undertakes to teach practice, must know thoroughly the theoretical part as well as the practical part. The man who undertakes to teach theory alone may get along with little, if any, knowledge of practice at all; but the man who undertakes to teach practice must know both the practice and the theory.

The idea of segregation, which was referred to, seems an excellent one, and it may be that the future will lead to it by a natural process of evolution. There has been some suggestion made, in fact, of technical schools which would be devoted to advanced technical teaching, either by taking men who meet higher entrance requirements, or by lengthening the course, In that way, by having the high grade men in a different class or school, we would be able to train high grade men so as to make them attain the highest efficiency.

Philip Torchio: Neglecting the all-important questions of individual talent, commercial acumen, and executive ability, which are mainly acquisitions by birth and surroundings, we may classify the students of engineering into two classes: one pursuing a college course to master the technical engineering knowledge, aiming to apply it directly in the conception, design, and carrying out of original engineering works; the other acquiring that knowledge as a means of securing a better class of employment or as a stepping-stone to commercial, industrial, or financial pursuits. Theoretically, the education of these two classes of students should be essentially different; the first requiring for his career a greater equipment of mathematical and theoretical training than the latter, for whom the practical side is of much greater importance. The measure of professional success in their respective fields of activity is in one case the amount of retainer and consultation fees, and, incidentally, social prominence; in the other it is the salary received or the increment profit secured by the commercial exploitation of any specific independent industry. If the two classes of students must be put through the same courses, I think that we would come to the conclusions reached by Professor Karapetoff, as a matter of expediency if not as a matter of choice. Professor Karapetoff's method will appeal most to the managers of industrial corporations and the majority of employers of engineering skill. It is a striking fact that most of the leading positions in industrial enterprises are to-day not filled by technical graduates. A few years ago about forty high officials of a large manufacturing corporation were seated at a dinner, and among all of them none was found to be a college graduate. As this corporation is considered here and abroad a model organization, such condition of affairs should command the earnest consideration of educators.

Conditions will change, I might say are changing now, but the progress is slow. We must, therefore, place our aims high, but not forget the local and present conditions, demanding highly specialized and practical knowledge. Our great centralization of industrial interests makes still more necessary a greater refinement of specialization than exists abroad. We may all deeply regret this narrow-gauge education, but we are leading the world into this condition. The great number of young electrical engineers are affected by these conditions. On the other hand, this very high degree of progress and specialization, combined with the importance and magnitude of the engineering work done in this country, creates a demand for exceptionally high engineering standards on the part of the relatively few leading men who pilot the heavy engineering and scientific work of the country. These different requirements make the problem of technical education more difficult. Now, if we must specialize, and we have the resources for doing it, why should not the colleges for electrical engineers also specialize, and equip themselves, some to turn out practical engineers fitted to fulfil the positions in industrial enterprises, and some to turn out electrical engineers with a much broader theoretical and scientific education, befitting the requirements of the broad engineering profession. The only obstacle that I can see would be an ill-placed jealousy among the different colleges.

I have no doubt that eventually we shall come to such results, as present indications point clearly that way. The majority of colleges will continue to bring into greater prominence the immediate practical applications of each engineering branch. On the other hand, a few other colleges more favorably situated will develop along more scientific lines, aiming to give a broad engineering education, possibly branching out into specialized electrical studies only in the last one or two years of the course.

I have the privilege of giving the experience of the Royal Polytechnic of Milan, Italy, which was started forty years ago along the lines of broad engineering education I have just referred to. About twenty years ago a course of electrical engineering was established through the private endowment of Carlo Erba, as an adjunct to the Polytechnic. The Polytechnic is a government institution but created mainly through the efforts of the late Professor Brioschi, a man of rare talent and ability, who imparted to the organization a good deal of his strong personality. The essential requisites for admission are the government certificate either of an eight-year preparatory course in a lyceum, in which classical studies prevail, or a seven-year preparatory course in a technical institute, where physical and mathematical studies and modern languages predominate. The average age of a freshman class at admission to college is about nineteen years.

The engineering course consists of five years, the first two being preparatory to all engineering courses, and the last three being sectionalized in three classes of civil, mechanical, and electrical engineers. The first two years cover a thorough study of the calculus and higher algebra, analytic descriptive, and projective geometry, general chemistry, mineralogy, physics, drawing, etc. In the next two years the mechanical and electrical engineers jointly follow, theoretically and experimentally, the studies of mathematical mechanics and applied mechanics, theory and design of steam, gas, and water power prime movers; design and calculations of parts of machines, resistances of materials and general construction, hydraulics, organic and inorganic chemistry, surveying, descriptive study of industrial plants, such as foundry and working of metals, cotton, silk and flour mills, etc.; technology of electricity, heating and ventilating, construction and operation of steam railways, etc.

In the last year the electrical engineers in common with the mechanical engineers complete the last courses in mechanics, hydraulics, mining, technologies, etc., and make two theses consisting of comprehensive detail drawings of a prime mover and plans of an industrial plant, and follow separately the course of dynamo and transformer design and operation, industrial applications of electricity, theory of electrical measurements and laboratory work.

The total lecture, laboratory, and draughting room work consists of 48 hours a week, 8 hours per day, approximately evenly divided, half for lectures and half for laboratory, draughting, etc. During the last years of instruction, the students under the direction of the professors carry out comprehensive efficiency tests of power plants and other industrial tests, measurements, and surveys, and make frequent visits to industrial plants throughout the country and to expositions, whenever feasible. The school discipline is very strict, and willingness and ability to do intense and sustained work is a requisite for remaining in the Institute. The teaching personnel for the theoretical subjects is made up of regular professors, while for almost all the engineering subjects the personnel consists of engineers, who, besides the educational work, have a large consulting engineering practice. This arrangement has worked out successfully in Milan, the main reason perhaps being the fact that Milan is the largest industrial center of the kingdom.

From his long experience with the polytechnic, Professor Brioschi has found that by an overwhelming majority the most successful careers are made by engineers whose early training and mind discipline had been along lines of broad classical and liberal education rather than those who in their early training had had a preponderance of practical studies like physics, mathematics, and modern languages. These results are rather striking, and, one would almost say, unexpected.

While realizing the difficulties of establishing comparisons and drawing conclusions for conditions vastly different, I do, however, believe that in this moment, when people under the pressure of a strenuous life are clamoring for simplified spelling, practical education, and other short-cut schemes, we owe it to our profession to place our aims at a high level; it is due to the intellectual standards of our leaders and the importance of our work in the community, and we should back up our position with doing all that is in our power to promote and advocate for this country, alongside but distinct from the highly specialized engineering schools, the evolution of a few centers of learning where the most liberal engineering education can be secured by those who by intellect, aspirations, and other favorable circumstances can afford to undergo a broader preparatory work and possibly a longer term at the college.

These centers, by attracting the best talents of the country to their educational staff, would indirectly benefit the other colleges by raising the standard of the whole profession, and would be a nucleus for that free intellectual and scientific activity which is the guiding spirit of the progress of this country.

President Stott: Thinking over this subject and listening to the discussion impels me to emphasize one or two points. The professors have asked us to be specific in criticism. The discussion to-night might be summed up by saying that there is a lack of general education of the freshman entering college. What is that caused by? The smattering of everything he gets in primary and high schools, a little of this and that, nothing taught thoroughly. The remedy for that is for our technical schools to raise the standard of their entrance examinations. If that be done, the other schools will be forced to raise their standards to meet it. The discussion seems to lean distinctly toward the point that engineering schools should teach fundamental principles and not engineering practice. I do not believe degrees should be granted until a man has been out of college for at least five years. In Great Britain doctors do not get their M.D. degree until they have been out of college and practicing for a number of years. I believe no one should receive a degree of mechanical or electrical engineer until he has had the practical training to make him worthy of such a degree. The weeding out process, which is inevitable at some stage, is a very hard problem; there are many reasons, financial and otherwise, why it should be almost impossible for a technical school to weed out students who, whilst qualified as students, are not likely to become engineers. If the degree in engineering were to be conferred only upon proof of work done, say five years after graduation, the stigma of the weeding out process would be taken away from the college; and when a man received his final degree in engineering, it would really mean that he was qualified to state that not only had he the necessary theoretical knowledge, but that he had also survived the refining process which sifts out 50 per cent. of our graduates in the first five years, leaving only those who are likely to become successful engineers.

Chas. P. Steinmetz: It appears to me that the question, how to get a thorough understanding of the fundamental principles, is answered in my paper. Drop out a sufficiently large part of the matter which the college now attempts to teach, so as to find time to improve the quality of the rest by thoroughly teaching it; that is, going over the subject over and over again, approaching it from different view points. After all, a clear and thorough understanding of a subject is gained only by looking at it from every possible point of view. For instance, the induction motor is not understood properly by considering it as a short-circuited armature revolving in a rotating field; it is not understood by considering it as an armature acted upon by a system of quadrature magnetic fields; it is not understood as a derivation of the direct-current shunt motor, combined with the transformer action transferring power to the rotor instead of leading it in by commutator and brushes; nor is it understood by considering it as an electric circuit revolving in an alternating magnetic field. It has to be looked at from all these view points before it can be understood. There is no time for this in the present college course. From my experience with very many college graduates, Americans as well as the product of foreign colleges, from far Russia in the West to Japan and India in the East, I am led to believe that any instruction is useless if it is not kept up to the end of the college course; that whatever the student has studied in one year and then drops, is of little benefit to him. To prove this, last year we gave our electrical engineering students shortly before graduation an examination in mathematics, in those branches which they had concluded in the sophomore year. The results were startling. This year the assistant professor of electrical engineering is giving one hour a week in mathematical subjects, to the junior as well as to the senior classes, with home work in applied mathematics. This has resulted in great improvement in the attitude of the students regarding the value of mathematics to the engineer.

I do not believe in text-books. I agree that a good text-book is better than a poor instructor. To me, a good text-book is merely a way of ameliorating a little the objectionable effect of a poor instructor, but a good instuctor is vastly superior to the best text-book.

It is gratifying to see the almost universal consensus of opinion, that practical familiarity should precede the mathematical theory of engineering, that the instruction should be built up in gradually widening circles through a study of the appearance, the action, the behavior, and the running of apparatus, and then gradually building up to an understanding of its operation, a study of the theory—ultimately culminating the structure with the most general, the mathematical equation and the most specific, the numerical calculation. A further development of this idea, carrying out this principle, is Professor Karapetoff's concentric method. I thoroughly believe in it. But there are difficulties in the way: experience proves that an intelligent and ambitious workman who has become familiar with electrical apparatus by operating it, or working in electrical factories, is anxious to find out the why and wherefore of a machine. Frequently the student is liable to be listless in this respect. When he has gone over the subject in a practical way first, and then goes over the same subject theoretically and more thoroughly, he is liable to neglect it because he thinks he knows enough about it. This means, to introduce better and more modern methods, we must start farther back, with the high school, and beyond the high school. A large part of the defects of the college education are really defects inherited by the college from the high school and the primary school and there is where the lever must be applied to improve conditions. The second serious difficulty is that before we can modernize and improve the education of the college boy we are obliged first to educate the college staff to the realization that conditions are not satisfactory. We are liable there to be met with statements as to what proper pedagogic principles and correct pedagogic methods are, and then we can hardly look for very much co-operation, from men which are satisfied that their way is the only right and proper method.

A. E. Kennelly (by letter): The questions under consideration are in one sense of great antiquity, although from another viewpoint they are of very recent origin. They are of great antiquity in the sense that electrical engineering is only a particular kind of engineering, and engineering is coeval with civilization itself. We have only to examine the pyramids of Ghizeh or a Roman aqueduct to realize that engineers existed thousands of years ago, and that such engineers must have received training for their work in some manner. On the other hand, the subject before us is of very modern growth in the sense that *electrical* engineering has made such recent development. Modern methods of instruction in electrical engineering are therefore the latest evolutions of educational training offered to meet the joint demands of the public, the engineering profession, and the engineering student body.

The Educational Committee can, no doubt, render to the Institute valuable service by collecting and collating information concerning the various systems and details of engineering educational methods adopted in different institutions of this country or abroad. It is, however, earnestly to be hoped that the Educational Committee will not seek to standardize engineering education, in the sense of pressing all institutions to follow as nearly as possible one and the same path, term, and system of engineering training. It is perhaps desirable that one and the same college degree in engineering should represent substantially the same amount of training or attainment on the part of the average student, so that it may be proper to attempt standardization in regard to the grading of one and the same degree. It seems undesirable, however, that all colleges or institutions training youths in engineering should grant precisely the same degree, or should offer identically the same training; should receive the same material, or should attempt to turn out the same finished product. It is here contended that what is more desirable is a wholesome diversity of aims, conditions, and training.

We know that in the world of mental activity as well as in the world of physical activity, achievement does not depend wholly upon training; it depends upon inheritance as modified by training. No great athlete, great singer, great engineer, or great worker of any kind was ever produced by training alone. We have the experience of mankind in all historical time to attest this fact. Men are born with an infinite range of capability for achievement in any given division of human affairs; some become eminent without any school or college training; while a great number can never become capable, no matter how much training they receive. All that we know is that training and education will increase each individual's power and capability, whatever that may be. An education is, therefore, an investment on the part of a student in time, money, vitality, and effort, for training to assist his inherited capabilities in his chosen life's work. It seems to be a biological law that the greater the inherent power of an organism, the longer the time and training required to bring this power to its greatest development. The highest types of mankind take the longest training with advantage. It does not pay to train the moderately gifted lengthily and extensively; it does pay to train the highly gifted long and thoroughly. The great bulk of the world's work must be done, and should be done by average men, and where there is room for one leader or colonel of a regiment, there is room and opportunity for creditable work to be performed by hundreds of average men. What is needed, therefore, is not that all institutions should attempt to turn out exactly the same type of graduates in engineering; they cannot, even though they try. Education should be graded to suit the needs of different individuals. We need many more privates and non-commissioned officers in engineering and industrial work than superior officers; and the country can be better served as a whole by offering a greater diversity of periods and types of engineering training. In addition to correspondence schools and evening schools, there is need of the training which can be offered by schools with schedules lasting from three months to six years. Such diverse trainings should be co-operative, in such a manner that a student entering upon a short course and showing ability to receive a longer and more thorough training should be aided in effecting a transfer; and, conversely, a student attempting too long a training should be aided in saving his time and energy by transferring to a shorter course. None of these different schedules would necessarily be superior or more worthy than another; they would all be equally important to the community as a whole.

H. B. Coho: We all know that fully 50 per cent. of the graduates from our technical schools and colleges receive their degree, not by any very brilliant actions or effort on their own part, but by the grace of their alma mater. These degrees are, therefore, heavily discounted, and their value is problematical. The average boy goes to college because it is an eminently respectable thing to do; he acquires a social standing, and an acquaintance, the value of which is well known. He enters the institution often on a diploma from a high school or preparatory school, which certifies that he has had a certain amount of opportunity to study a given quantity of subjects, and ought to know something of them.

To my mind the degree of a technical school ought to mean something absolutely, or else it should not be given; and I am firmly convinced that the degree of electrical engineer should be conferred by the American Institute on such of their members as can pass a given examination, and show at least three years' practical experience in the line of their chosen profession, this degree should be open to the artisan as well as to the college-bred man that can qualify.

My opinion is that the remuneration of college professors has comparatively little to do with the results, as I doubt very much whether our captains of industry would make good teachers, and, *vice versa*, whether our teachers would make satisfactory captains of industry. To make a success of anything, a man must devote his time and thought to the subject in hand, without heeding the money recompense. The mere lust for money is easily satisfied, but the lust for power and achievement cease only at death.

Before a piece of steel can be sharpened it must be tempered; so with the human mind, the mind must be trained before it is ready to receive the finer impressions.

As Dr. Steinmetz has said, then, the improving of the lower grades must be carefully attended to, The boy is the father to the man, and we all know that it is impossible to obliterate entirely impressions received during the first ten years of life, therefore, the importance of giving care and attention to the primary and secondary grades in our public schools is apparent.

To my mind, our school system should be so devised as to give a pupil from the beginning individual attention, treating him as a unit, and not as a class, and keeping a careful record of his work throughout his whole school life, so that when he reaches the age where a selection of occupation is to be made he can be advised and guided. By making his entrance to college or technical school dependent not only upon his ability to answer a certain list of questions, but also on his record, we shall greatly improve upon the material which our teachers will have to deal with; the product of our educational institutions will then be men, capable of taking up life's problems in an intelligent manner.

A. S. McAllister (by letter): The fact that a large percentage of the graduates from engineering colleges prove unsuited for engineering work, as stated by a speaker who is exceptionally well qualified to make observations, is one that has as yet not received the proper amount of consideration from those interested in the education of our boys. The present writer believes that the college courses and methods of instruction furnish only a small part of the cause for the result. During my short teaching experience, I became thoroughly convinced that many of the students that came under my observation were much better qualified for some line of study different from engineering rather than for engineering itself. The fact that a student makes indifferent progress in engineering does not prove either that he is lacking in brain matter or that the method of engineering instruction is incorrect; in many cases his parents or the advisers of the student during his high-school days are at fault. It is absolute folly to attempt to make an engineer out of a student who during his high-school days shows not only no taste for physics and mathematics but is innately averse to all studies that appeal to the reason rather than to the memory. There are students who display no marked inclinations along any certain line of study, while there are others who seem to enjoy all lines. The latter, however, are the exception rather than the rule. A fact that should always be kept in mind by those in position to decide whether certain boys shall attempt engineering college work or take up other duties immediately after leaving high school is that a college can develop latent talents but that it cannot put brains into an empty skull; it cannot make an engineer out of a boy whom nature has deprived of well arranged reasoning faculties. It would obviously be very improper for anyone to claim that an engineer, like a poet, is born and not made. However, it can be truly stated that the chances for success are infinitely greater for that boy who selects a career in conformity with his natural talents, than for one who adopts a profession merely because his parents consider it one in which the average compensation is comparatively high. Many of the third-rate lawyers and doctors of the present day could have made excellent engineers; many of the present day inefficient engineers could have become first-class doctors or lawyers. It is an absolute injustice to the student to allow him to undertake one line of work for which he has no talents, and thereby permit his natural talents which lie along other lines to remain dormant. The entrance requirements should be arranged in such a way as to determine for what line of work a boy is best suited, in order that he may secure the maximum good from the time spent in college, and the instructors may obtain the best results from their labors.

W. S. Franklin (by letter): My hobby is mental arithmetic. The ability of a student to follow a simple physical argument depends vitally upon his power to hold numerical relations in mind, and the greatest difficulty that I encounter in my work of teaching elementary physics arises from lack of this kind of arithmetical sense on the part of the student. For many years I have tested my junior students with the question: "When does a growing thing reach its greatest size?" I have found but one student in all my experience who was ready with the simple arithmetical answer: "When it stops growing". And yet nearly every man in every class could have filled a blackboard with algebraic formulas in response to a formal question concerning the maxima and minima of an algebraic function.

In discussing the ballistic galvanometer, one arrives at the proposition that the rate at which the suspended needle gains angular velocity is proportional to the rate at which charge flows through the coils, from which one argues that the total angular velocity gained is proportional to the total discharge. I always illustrate this point by asking the class to consider one man who saves money ten times as fast as another, whence it may be argued that the one man must always have ten times as much money as the other, if they get an even start, and then I ask the class what this argument is called, but never yet have I found a single student who had a sufficiently simple idea of calculus to know that this arithmetical argument is called integration.

I have always had a desire to use the algebraic forms of calculus in my teaching of elementary physics, but the weakness of most students in the simpler branches of mathematics and the almost universal lack of arithmetical sense (the holding of numerical relations in mind) has forced me to the conclusion that it is ridiculous at the present time for any teacher to attempt to use calculus in the handling of any subject in the class-room. I think it is no exaggeration to say that ninety-nine per cent. of the technical graduates with whom I have conversed have admitted their total lack of understanding of the subject of calculus when they took it in the technical school. If most of us did not stand in awe of mathematics, such a state of affairs would lead us instantly to the conclusion that something was radically wrong, but it seems that most men are still imbued with the idea expressed many years ago by the great English mathematician, Sylvester. Sylvester showed an unusual aptitude for mathematics while still an undergraduate, and he said that he was pointed out by his mates as a man who, like Dante, had seen Hell, the idea being that mathematics was not supposed to be understood by the great mass of students who were required to study it. Now I contend that calculus must be understood by the great majority of men who study it, or it must cease to be taught; and I believe that the reduction of calculus teaching to the plane of old-fashioned mental arithmetic would go a great way towards meeting this situation.

O. J. Ferguson (by letter): A man goes to college to save time by concentration. All that he acquires there can be obtained elsewhere and by other methods, but the operation of these other methods is subject to so many interruptions and diversions that the efficiency rate at which the work is done is low.

No college training of a few years can fit a man to occupy positions of great engineering responsibilities. It must be augmented by experience. During college life he is considering the available results of experience of others, but man is so constituted that he must learn ultimately by his own personal contact with facts.

Of these two components of his training we are discussing the one which comes under the direction of instructors. The most important things to be considered therewith are, in the broadest sense:

1. Methods of thought.
2. Fundamental truths.
3. Allied subjects.
4. Average data.
5. Experience—enough to serve as illustrations and as "labels" for theory.

No engineer who comes into contact with men recently graduated from colleges can fail to note the general inability of their minds to grasp important details, sift, summarize, reason logically, and analyze keenly. All minds are not equally endowed in these respects, but training should bring out whatever exists of these all-important requisites to the engineer.

Mathematics is the purest of logical and analytical reasoning, and, considered even wholly aside from its utility, should be placed in the first years of college work and never wholly omitted later in the course. Its value lies in the fact that it permits clear, concise, definite statements, and demands proof of every step from its "Given" to its "Q. E D". It should progress from the pure to the applied, and to broad engineering practice which is richer in problems than is the mind of any author of mathematical text-books.

Facts are of several kinds. Truths, facts of to-day, facts of yesterday, and things that never were so. Fundamental truths should be distinguished from current practice. Keep up with the times but do not lead students to accept offhand the things of to-day as the standards of to-morrow. One can devote too much time to practice to obtain breadth of view.

Allied subjects should be taught, not from the electrical engineer's view, but broadly and carefully though not in detail from the point of view of the specialist. For, no matter what we are using or are not using now, the future will demand more from us.

Average data of existing normal practice should be analyzed for fundamentals. Machine shop and laboratory work are beneficial so far as they serve to clarify ideas of machinery, circuits, and power development, transformation and measurement, and to illustrate methods of reasoning in the study of problems. As before indicated, they are the pictured labels attached to carefully stored bits of information and are to be used as identification marks in selecting such data for comparison with subsequent experience. A great deal of the time spent in manual training, etc., is of little value compared with what might be accomplished by a better use of the same time. Personal experience should not be allowed to intrude itself into any curriculum at the expense of concentration upon the main line of thought.

As for the order in which certain studies are met, I believe it is better to prepare the broad foundation first with its tendencies toward habits of scientific reasoning and research,—painstaking and deliberate. Theory can at first be stripped of its "negligible quantities" and is still intricate enough for the beginner. Practice can never eliminate these minor influences which serve to hide to a greater or lesser degree the principles sought, although they may not seriously influence the problem at hand.

C. O. Mailloux (by letter): The lecture system is objectionable, in my opinion, so far as, and to the extent that, it robs a student of the time and the energy requisite to study his notes properly, because too much time and energy have to be consumed in taking the notes and, especially, in correcting, rearranging, completing or rewriting them; in a word, in making them "fit" to study. A certain amount of "going over" the notes, on the part of the student, is, in my opinion, desirable; but much of its beneficial effect is lost when the notes are incomplete and incorrect because the student was not able to follow the lecturer. Unfortunately, this occurs much more often than ought to be the case. It is for this reason that the syllabus and book of reference becomes valuable, if not indispensable, as a means for filling the gaps and voids, and of mending lame notes containing incomplete or incorrect diagrams, formulas, etc. It does seem as if much of the student's time and energy, that now has to be devoted to correcting and amplifying his notes, might be devoted to studying them. After observing and studying carefully the methods of some forty or more lecturers on technical subjects, from the dual standpoint of student and teacher, I am of the opinion that the shortcomings of the lecture-system of instruction are more often due to the lecturer than to the lecture-system; and that it would be only necessary, in many cases, to improve the method of the lecturer, in order to improve the results of the system. The ideal system, in my opinion, is a lecture-system, in which the lecturer, either by dictation or by writing out in sufficient detail on the blackboard, or by means of a good syllabus, simplifies the student's task of getting accurate notes, and, at the same time, allows him time to follow the reasoning, demonstrations, and discussions presented. It is too often the case that the student is so busy with the mechanical work of taking down notes, that he is totally unable to follow, much less to absorb and digest, the subject-matter presented. In such cases, it is obvious that the method of teaching by lectures is much inferior to that of teaching by the text-book system. As already stated, however, the fault lies more with the particular method of the lecturer than with the lecture-system.

H. W. Blake (by letter): On one point all engineers are agreed, namely, that it is impossible to crowd into a four-years' course all of the instruction which the young electrical engineer will find useful after graduation. If this is true at the present time, it is evident that as the art advances year by year it will be necessary still further to circumscribe the number of subjects included in the required courses. This will involve yearly additional sacrifice of instruction in those branches, which are classed by one speaker as " cultural and scientific " rather than purely technical.

The engineering schools are now attracting many men whose fields of activity after graduation are almost as varied as those of the graduates in the academic or arts department. These men would formerly have matriculated in the older college course, but the inclusion into so many lines of industry now of engineering principles makes an engineering education a desideratum. At the same time, a knowledge of the purely technical branches of the subject is not so important for many of these students as a good acquaintance with such topics as business-law, rhetoric, and modern languages, and the ability to meet the political and economic questions which are apt to arise in the administration of engineering undertakings.

The technical educator is, then, face to face with a serious dilemma. Should he confine his curriculum to the purely technical studies which experience has shown require the entire time of the undergraduate to master, or should he subordinate some of them to those cultural and scientific branches desired by a large number of men entering the technical schools yearly? The answer to this question is really dependent upon a decision whether it is possible to introduce electives in an engineering school to the same or nearly the same extent as in the arts course. One reason advanced for not following this plan is the expense of supplying the varied instruction, but this hardly applies in universities, where these outside courses are taught in other departments. Another objection has been the question of degree, because the title of engineer, civil, mechanical, or electrical, awarded at the end of the course, is generally considered to imply familiarity with certain prescribed studies. This objection may be valid and may not. Certainly, however, the tradition is not as venerable as that which limited the degree of B A. to a college course which should include at least two years of study in Latin and Greek. This requirement is no longer in force in many leading universities. If necessary, the engineer's degree could be reserved for a post-graduate course along certain well-defined lines. The chief point is that the electrical engineering industry is now calling for many men whose training should primarily be along engineering lines, but who also require certain instruction which the technical schools cannot give unless they incorporate into their curricula a liberal system of electives.

Dugald C. Jackson (by letter): Many excellent words are said in the two brief papers which have been presented by Mr. Scott and Dr. Steinmetz, but I am compelled to take the view that neither of the papers makes any constructive suggestions which may lead to an advance in engineering education. Perhaps the nearest suggestion that comes to that point is to be found on the first page of Dr. Steinmetz's paper, where he refers to the importance of close coöperation between the electrical industries and the engineering colleges. That coöperation is growing up rapidly as a matter of necessity, but it has heretofore been more or less undirected, and I had hoped that the papers of this evening would give us some suggestions for making more out of that effort. This is surely an important question for the Educational Committee carefully to consider and digest with a view of bringing up concrete and constructive proposals Dr. Steinmetz makes the interesting statement that the existing coöperation probably constitutes the strongest feature of American engineering education. I am in partial agreement with him, but I am by no means in agreement with what I understand to be his implication that the present coöperation is as effective or intimate as it should be. I will not here undertake to enter into the enumeration of the reasons for my views, but will perhaps undertake to do so at some later date.

In this connection I wish to call attention to Mr. Scott's statement that a fairly intimate intermingling of college work with practical work will be found to conduce to the efficiency of each, and I wish to express my hearty sympathy with that statement. I believe that much can be done in the way of improving our present electrical engineering education by increasing and strengthening the kind of coöperation which is suggested in this sentence of Mr. Scott's.

Mr. Scott's paper seems to indicate that he stands for Professor Karapetoff's plan, which has been dubbed the "concentric method", but I am sure that Mr. Scott could not be the unqualified supporter of that plan had he submitted Professor Karapetoff's proposals to a detailed analysis. The plan which has been presented under the name of the "concentric method" is one which naturally catches the attention of a busy industrialist, and it may hold his attention until the conditions of his industrial work will give him leisure to analyze carefully the processes described. Then he will find that the details proposed by Professor Karapatoff are subject to serious criticism as being in opposition to the basal tenets of pedagogy, though the general plan does not differ very much from the plan which is in operation, with marked success, in several of the best engineering schools. Given time on my part and leisure on the part of Mr. Scott, I will undertake to convert him to my view on this matter, with the understanding that that conversion will be permanent because it will be based upon sound reasoning.

The defects which Dr. Steinmetz points out in the second page of his paper will be admitted by thoughtful and experienced teachers of engineering, but it is happily a fact that these defects are being slowly cleared away. The rate of improvement is so slow as to be exceedingly discouraging when considered year by year, but the aggregate improvement which has been made in the past decade is so marked as to give good ground for optimism in respect to this part of engineering education.

In this connection I wish to point out that Dr. Steinmetz seems to possess a misapprehension in respect to the ideals of some of the better engineering schools. It cannot be properly said that the students in all of the engineering schools are allowed the opportunity to take up the important basal subjects and are then intentionally allowed to drop them without succeeding drill in their applications. The fact is that the mathematics, the chemistry, the physics, the applied mechanics, and the more distinctly professional studies following thereafter should be closely correlated and dovetailed into each other, the order of the work being planned with due consideration of the coördination of the subjects; and care is taken to effect this coördination in certain of the engineering schools. Dr. Steinmetz is probably right in criticising the arrangement of most electrical engineering courses from this point of view; but, unquestionably, the ideals lying behind the teaching in several of the electrical engineering courses give due and full consideration to these factors; and, indeed, no course can be carried on with fair consideration of the best known principles of pedagogy without including provisions for these factors. The worst features of many of our engineering courses have arisen from the fact that so much of their work has been introduced without consideration of the pedagogical sequence of the parts or the relation of each part to the whole.

Mr. Scott ventures the prediction that the solution which will find the most general acceptance of the problem of what is the best engineering education, will be that which gives to each student the training that fits him for his best individual development. In these words Mr. Scott has stated an important principle in education, and he is to be heartily thanked for putting the matter so plainly. To get a fundamental principle clearly in mind is often half the battle. But Mr. Scott leaves us still groping, because he gives no adequate indication of the direction in which engineering courses may be improved for the purpose of gaining the goal which the principle lays down. The same may be substantially said of Dr. Steinmetz's paper. Dr. Steinmetz remarks that the present condition in the industries, wherein men who have never had a college education may rise ahead of college graduates, would be impossible if our engineering courses gave what they should, namely, an intelligent understanding of electrical engineering subjects. But the difficulty under which we now labor is to lay our finger on the specific improvements which can be and should be effected for the purpose of affording this intelligent understanding of electrical engineering subjects that Dr. Steinmetz asks for. What the engineering schools need now is careful analytical scrutiny of their processes of work, and constructive suggestions for changes which will bring about improved results.

I believe that the better engineering schools have a lively understanding of their defects, and a well-developed desire to overcome them, but a difficulty resides in determining what improvements will bring the wished for results. Experiments in education generally require years of trial before their effects can be clearly discerned, and experiments must therefore be made with caution to prevent taking any backward step.

I wish to say a word in regard to the remarks of two or three other members who entered into this discussion. In respect to Mr. Ferguson's remarks, I believe that I can say that I heartily agree with the whole of his presentation; and I also want to express my appreciation of Professor Clifford's admirable presentation of the requirements in engineering education. I would like to emphasize, more than Professor Clifford's remarks emphasized, the necessity of adding those things which lead to the education of judgment; and my acquaintance with Professor Clifford assures me that he probably agrees with me on this point.

Mr. Stillwell directs attention to the proposal that the ideal education for engineers is going to be brought about by the plan which is now being shouted as a shibboleth from the housetops—an arts course first and an engineering course afterward. I do not believe that this is a solution of the difficulties which are outlined in the papers of the evening, and I believe the plan was originally conceived by men who are unacquainted with the necessities of engineering education. These men may have a profound knowledge of the great results that come from a proper pursuance of the old-time arts course, but this does not give them the experience or the power which makes them sound leaders in the problem of engineering education. I believe it is a misfortune that such admirable engineers as Mr. Stillwell are willing to lend themselves to the promulgation of this plan without a full and complete analysis of its results. I heartily agree that an engineer needs to be a broadly and completely educated man; but where two horses are to be driven it is better to drive them side by side (in parallel) rather than in tandem, if one aims at effective power and not merely at showy results. It seems to me that the engineering course, to be fully effective, should include the physics and the chemistry and the mathematics and much of the general studies in the engineering school, and subjects such as political economy, history, and the languages may be appropriately carried out to the end of the course. This, indeed, is a factor which I understand Dr. Steinmetz approves, and it is this suggestion contained within the so-called "concentric method" which I presume attracts Mr. Scott's friendly attention. The failure of the concentric method lies distinctly in the repetitions of work which it recommends. There may be a real utility in the modified proposition which is now beginning to gain vogue amongst the best thinking men of the engineering schools, and also of the literary and classical colleges, which proposes that students shall spend perhaps two years under the influences of the arts course and shall then spend four years under the conditions of the engineering school. This would make the engineering school base its entrance requirements upon attainments gained by the students from two years of the arts course in college of university, and the plan comprises many factors which indicate its utility as an educational plan. The plan urged by Mr. Stillwell calls for three or four years in the arts course and then for two or three years in the engineering school; but this abbreviates the engineering course to a degree which makes the joint work relatively ineffective, besides giving the students a misapprehension of the relative importance of their historical and literary studies compared with their technical studies.

DISCUSSION ON "NOTES ON ELECTRIC HAULAGE OF CANAL BOATS", AT NEW YORK, MARCH 13, 1908.

(Subject to final revision for the Transactions.)

Richard Lamb: This seems an opportune time to discuss this subject, for the public at large seems to be giving considerable attention to the subject of the waterways. The government officials at Washington are suggesting that there be legislative enactments in the matter of the water powers, so that these powers can be conserved for future use. Undoubtedly, in many cases these water powers will be used to propel boats, especially if such work as has been illustrated here to-night is carried to completion.

I do not agree that efficiency can, to a great extent, be disregarded. As engineer for the company that contracted to tow canal boats on the New York State canals, I had occasion to investigate, in a practical way, the subject of canal-boat towing. The results of the tests made on the Erie canal at Tonawanda, N. Y., showed that the cost for towing a boat from Albany to Buffalo by mules, steam propellers, and by electric motor were, respectively, $42.24, $17.60, and $15.32, with relative speeds of 1.3 miles, 3 miles, and 3.6 miles per hour. In order to compete with the principal motive power now in use, the mule, great care should, therefore, be taken to obtain the most efficient motor, from both mechanical and electrical standpoints.

In this country attempts have been made to utilize the towpath for a railroad bed, and to tow the boats by standard locomotives. These tests proved unsatisfactory, because of the necessary slow speed at which the boats had to be towed. The dead load and the fuel consumption of a locomotive going only three miles an hour made the standard locomotive very inefficient for this purpose. A low rate of speed is the governing factor in canal-boat towing. This attribute is inherent, because of the limited distance between the bottom of the boat and the bottom of the canal.

It sounds like a paradox to say that when a canal boat is pulled at its maximum speed, it stands still. The bottom of an Erie canal-boat is nearly flat and is 17.5 ft. wide. The distance from the bottom of a loaded boat to the bottom of the canal is one foot. Conceive of an area equal to the width of boat and the distance from the bottom of the boat to the bottom of the canal as being an orifice through which water must flow. The area is 17.5 sq. ft. When the boat is standing still there are 12,827 gallons of water under her. At 6 miles per hour, 1166 gallons per second would have to pass through 17.5 sq. ft. of sectional area, if the boat remained as it was; but as a matter of fact the boat settles as the speed increases, and therefore the sectional area under the boat decreases, making it impossible for so large a quantity of water to pass under the boat in so limited a time. Hence the water passes to easier channels, to both sides of the boat, until there is no water under the boat and it stops. Therefore, as soon as the maximum speed is reached, the boat stops.

An intumescence of the water at least one-foot high forms about a loaded Erie canal-boat when going three miles an hour. This water, not being able to pass under the boat, passes to either side, making a wave. At four miles an hour, a loaded canal boat on the Erie canal generates dead water under the stern so that it is practically impossible to steer her, and the curves on the canal make navigation at this speed difficult and dangerous. I consider that after equating for first cost and maintenance of canal and electric towing plant, and the maximum carrying capacity of boats, that a speed of three miles an hour is the greatest that should be sought. The wash of the canal bank, caused by the waves generated by a boat going more than three miles an hour is no inconsiderable factor in maintaining the canal.

In the paper under discussion all the records of the draw-bar pulls are referred to the components of the parallelogram of forces, the resultant of which would be the tow-line. I do not see the object of doing this. I think that a comparison of the actual tow-line pulls would be more satisfactory, especially as the angle made by the tow-line with reference to the course of the towing motor would vary but little.

The tests recorded, show that a tractor weighing 6493 lb., and getting its tractional friction from the pull on the tow line, is not so efficient as a mining electric locomotive weighing 16,000 lb. The tractor exercised a greater resistance to its own propulsion than a mining electric locomotive of over twice its weight. The experiments demonstrated that a " tractor must have a pressure made upon the wheels equal to the weight of a locomotive that will give similar traction ". It is evident that a tractor that gets its tractional friction independent of its weight, or independent of a friction that would impede its progress to the same extent as that of a locomotive of sufficient weight to give a similar traction, would be much more efficient than either of the types of motors tested. In designing the motors for the tests on the Erie canal, and the Finow canal in Germany, I succeeded in producing an efficient motor, working independently of its weight. The lighter it can be built, the more efficient it becomes. These motors are described and illustrated in the New York State Engineer's reports, also in the TRANSACTIONS of this Institute and those of the American Society of Civil Engineers.

The motor tested on the Finow canal in Germany weighed 1984 lb. It carried a 5-h.p. motor. It pulled the loaded boat with ease at the speed for which it was geared to run, namely, 2.5 miles per hour. The tow-line pull was 575 lb. The electric motor did not consume its full quota of watts. This was done on a cableway track. If a low I-beam track were used, the efficiency would have been greatly increased, as the motor would not have had grades to climb on approaching the supports. With such a track, this towing system would be ideal, especially if single-phase current were used for the electrical transmission.

C. P. Steinmetz: During the rapid expansion of our railway system, the canals had to take a rather secondary position, but it is gratifying to know that general interest in canals and in water transportation is reviving, and that the government is considering the improvement of the Mississippi waterway, and that the state of New York is rehabilitating the Erie canal.

What would be still more interesting than the paper is, not merely a comparative test of two rival systems, but a comprehensive paper covering the subject of canal haulage; that is, a comparison of the relative advantages, efficiencies, financial economies, etc., of the different systems of electric haulage, of steam propulsion, and of other methods, which have not been mentioned. Other methods are the chain drive, where a chain is laid at the bottom of the canal or river, and raised up to propel a boat, carried over a drum, and dropped again. I understand that this system gives good service abroad. And let us not overlook the *mule*. Mule propulsion of a canal boat appears to be a rather antiquated method, but we may find, nevertheless, that mule power, is, after all, under some conditions, the most economical form of drive. Comparing the cost of electric power per ton-mile as given in the paper with the cost of maintaining the same mule power, I should not be astonished to find that under the average conditions of canal haulage, the mule is the cheaper power. I am told that mules are cheap to buy and maintain, and are long-lived.

In systems of canal haulage a condition essentially different from that of the railroads has to be met, in that most of the canals are public highways; that is, any boat has a right on them just as a cart has on a public street. A railroad company has exclusive control of its right-of-way. Electric propulsion, then, must not interfere with mule or steam propulsion, or any other established method of propulsion on the state or national canals. Financially, the most serious feature is that canal traffic, in very many cases, is extremely light and intermittent. It exists only for part of the year, and the traffic varies considerably from year to year. Any equipment installed to take care of the maximum traffic would lie idle a part of the year, and might be very uneconomically used during some years. Under such conditions an electric system may be rather uneconomical. One of the chief advantages of the canals is the greater independence of the railroad which they confer.

It appears to me, therefore, that to show a superior efficiency to other forms of haulage, the field which electric haulage would cover, the traffic which it would take care of, would not be the traffic which exists now on waterways like the Erie canal, but a new form of traffic which would probably be created. The trolley lines have not taken the traffic of the steam railroads, but built up a new traffic; and I can well see that it might be possible to establish a profitable system of electric haulage on the numerous waterways of the country. A further careful investigation of the subject would be of considerable interest and of great benefit to the engineering profession.

L. B. Stillwell: The comparison of the two traction engines that we have made has resulted in certain determinations of comparative energy required and of actual energy required which have an application wider than we have attempted here to give them.

As regards efficiency of the contrasted machines, while the difference in favor of the locomotive is not controlling, it should not be minimized too far. Table 5 evidences clearly that from the mechanical standpoint the tractor is materially less efficient than the mining locomotive. While the difference in losses is small in comparison with the total energy utilized, it is large when expressed in terms of losses. For an effective pull of 2000 lb., for example, the mining locomotive loses an equivalent pull in the machine equivalent to 400 lb., while the best of the tractors loses 600 lb. The lesson to be drawn is that the tractor needs mechanical improvement.

With reference to Dr. Steinmetz' remarks in regard to a broader treatment of the subject than is attempted in this paper, I would say that in the course of the same investigation upon which our paper is based we studied the economy of the electric haulage system as compared with haulage by mules and established, to our own satisfaction at least, that if a canal is worked at anything approximating its full traffic capacity, electrification will pay handsomely.

In the case of the canals of the Lehigh Coal and Navigation Company, assuming some improvements in certain locks and an increase of traffic to a point approximating the full capacity of the canal, we estimated that the cost of operation, including all capital charges, could be reduced below one-half a cent a ton-mile. The grand average cost of freight transportation in the United States by railroads slightly exceeds 4 mills per ton-mile without any capital charges, locomotive repairs and renewals, being charged generally against cost of operation. It is safe to say, therefore, that if these canals were worked to their full capacity, even with the small barges now employed, the cost of transporting freight per ton-mile will closely approximate the average result attained in steam railroad practice to-day. With larger barges and larger locks, the cost of transportation would be further reduced; but everything depends, as Dr. Steinmetz suggests, upon the amount of traffic. The occasional mule is a proper engine when the traffic is very light, but if the traffic can be worked up to a reasonable extent it will pay to electrify. The capital costs when divided by a very large number of ton-miles per annum are reduced to so small an amount that they are absorbed by the general economies resulting from electrification.

DISCUSSION ON "NOTES ON RESISTANCE OF GAS-PIPE GROUNDS", AT NIAGARA FALLS, JUNE 26, 1907.

F. J. Hoxie (by letter): In 1906 and 1907, I made a series of measurements to determine the amount of protection that could be expected from pipe and plate grounds on lighting systems. The paper by Mr. Hayden shows considerably less resistance for the same area of earth contact than is indicated by my measurements. This is probably due to a finer soil and a greater amount of salts dissolved in the ground water, for plates only a few feet apart in different kinds of dirt and in the water of the same pond show large differences in resistance. References to the resistance of ground plates in electrical literature are generally indefinite, but they give the impression that a copper plate of moderate dimensions buried in permanently moist earth will have a resistance of about ten or fifteen ohms. As this is greatly at variance with the facts, in some parts of Rhode Island at least, the following measurements may be of interest.

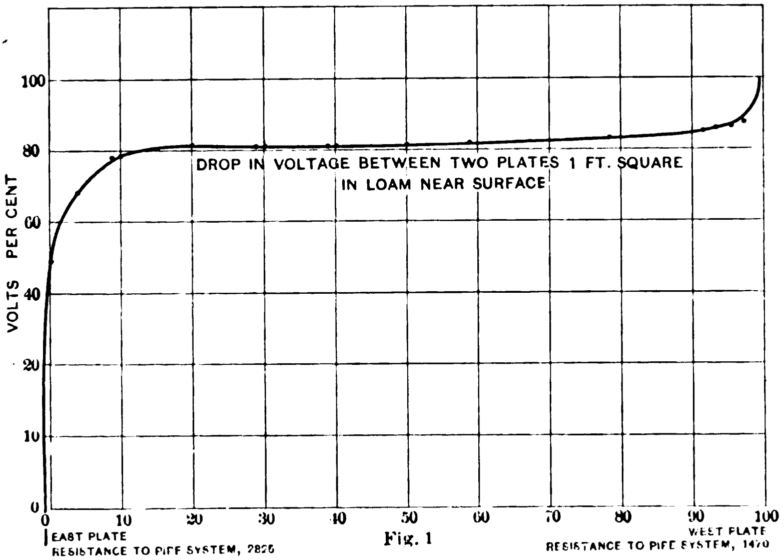


Fig. 1

These measurements were all made in Rhode Island, in a soil very free from soluble minerals. Most of them were made where there is an underlying ledge of granite about 60 ft. below the surface and the ground water level is just above this ledge. Between the ledge and the surface loam the soil is mostly silica, sand, and small stones of varying sizes, unevenly mixed and apparently the result of a violent movement of water in past ages. The well-water contains about 100 parts of mineral matter and the river-water about 30 parts in 1,000,000. The surface loam is of a reddish color, somewhat sandy, and from one to three feet thick.

The resistance of plates or pipes buried in this soil varies so greatly from the figures mentioned above that it is evident that a copper plate of any reasonable size is not a safe ground for a lighting system carrying large currents at moderate potential. By referring to the table of measurements, it will be seen that the resistance of a metal plate one-foot square in the surface loam is about 2000 ohms, in the underlying sand about 11,000 ohms, and in the ground water at the bottom of a well about 300 ohms. Rainy or dry weather makes comparatively little difference to the resistance, except in case of the sand.

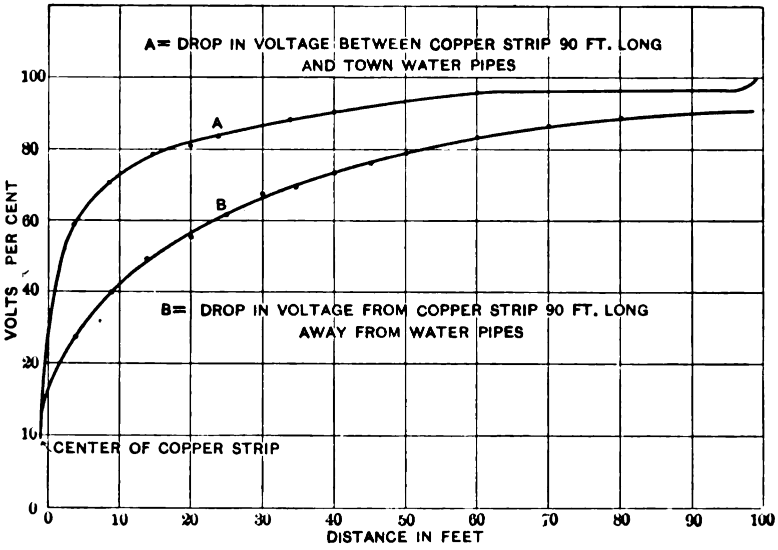


FIG. 2

As the area of a plate is increased, the resistance is not proportionately diminished, but in about the ratio of the square root of the areas; but when a number of small plates widely separated are connected to form a single ground-connection, their separate conductivities are added, as shown by the resistance of 13 ohms of the thirty 1.25-in. pipes driven into the ground five feet at intervals of 300 ft.

The curve in Fig. 1 shows the drop in potential between two plates one-foot square buried near the surface of the ground 100 ft. apart. Fig. 2 is a similar curve of the drop in potential, between a copper ribbon, buried in a straight line 90 ft. long and one foot under the surface of the ground, and a town water-pipe system.

Greater depth does not necessarily decrease the resistance of a ground plate. In this location the reverse is true until the ground water is reached, as is shown by the resistances of plates in the surface loam and in the sand where the loam has been removed. The conductivitiy of ground plates or pipes is apparently governed by the laws of solutions of electrolytes as to variation with temperature and concentration. The coarseness of the soil in contact with the plate also affects the conductivity, as the area of contact is greater with a fine than with a coarse soil, unless the plate is below the ground water level.

The method of measurement used was as follows: the 60-cycle, 104-volt, public service current was grounded on one side to the public water-pipe system; the other side of the circuit was connected to the ground to be measured through a one-ampere portable ammeter. In some of the high-resistance measurements a 10-to-1 transformer was used. The voltage was measured with a portable voltmeter. The curves were made by connecting the two ends of a german-silver wire 100 ft. long with the two sides of the circuit. The ground plates to be measured were connected as near as possible to the ends of the wire. A telephone receiver was used as an indicator, this being attached on one side to the resistance wire by a movable contact, and on the other side to a rod which was put in the earth at regular intervals between the two plates, the point of equal voltage being found on the wire and the readings plotted as per cent. of the impressed voltage.

Resistances between the town pipe system and the following:

Plate 6 ft. 2 in. by 3 ft. in still water bottom of the Pawtuxet river	32	ohms
Plate 1-ft. square in still water bottom of the Pawtuxet river	132	"
Plate 1-ft. square in current in bottom of the Pawtuxet river	232	"
One cu. ft. Pawtuxet river water between two opposite faces	2800	"
Plate 1-ft. square in rain water cistern	197	"
Plate 1-ft. square in stoned well 45-ft. deep	280	"
Plate 1-ft. square in cement cylinder well 50 ft, deep	406	"
One cu. ft. well water between opposite faces	437	"
Plate 1 ft. by 2 ft. on ledge in bottom of Pawtuxet river, rapid current	324	"
Plate 1-ft. square in stoned well 40 ft. deep	310	"
Plate 6 ft. by 2 ft. 3 in. in three bushels coke 6 ft. deep in moist black loam	113	"
1.25 in. gas pipe driven into gravelly ground about five feet	630	"
Nail driven into apple tree about 6 ft. above the ground	3855	"
Wire around and forced into bark of apple tree limb 7 in. in diameter	3030	"
Seven 1.25 in. pipes 5 ft. long and 300 ft. apart in swampy ground	15	"
Ten 1.25 in. pipes 5 ft. long and 300 ft. apart, gravelly ground	53	"
Two 1.25 in. pipes 5 ft. long and 300 ft. apart, gravelly ground	272	"
Thirty 1.25 inch pipes 5 ft. long and 300 ft. apart all kinds of ground	13	"
Plate 1-ft. square in contact with mud on top of frozen ground	3600	"
Plate 1-ft. square in sand, surface soil removed weather dry	11000	"

Plate 1-ft. square in sand, surface soil removed after hard rain	2947	ohms
Average of eight plates 1-ft. square in surface loam	1940	"
Plate one-foot square under shed, ground saturated with brine, soil as above	175	"
Copper ribbon 0.5 in. wide and 90 ft. long buried in surface loam 1-ft. deep and in a straight line.		
June 10, after a heavy rain	107	"
June 23	110	"
October 6	121	"
October 7, after heavy rain	118	"
November 12, morning after heavy rain clearing up	107	"
November 12, noon clear	117	"
November 13, ground slightly frozen on top	122	"
December 2, ground frozen	142	"
March 17, 1907, ground frozen deeply and covered with snow	155	"
Plate 1-ft. sq. in medium coarse sand bottom of warm cellar	9600	"
Plate 1-ft. sq. in fine clay-like sand bottom of warm cellar	2160	"
Plate 1-ft. sq. in red sandy loam in bottom of warm cellar	716	"
Plate 1 ft. sq. in sifted red sandy loam under building not heated	1550	"
Plate 1-ft. sq. in highly fertilized garden loam	860	"
Plate 1-ft. sq. in very fine sand in garden under surface loam	1000	"
Plate 1-ft. sq. in red loam just under the grass roots of orchard	2300	"
120 ft. No. 12 copper wire in straight line about 3 in. under the sod	220	"

Except the river and pipe grounds, the above measurements were all made within a few hundred feet of one another, with the geological conditions practically the same, and are mostly averages of readings made between February 1 and June 1, 1906.

J. L. R. Hayden (by letter): Mr. F. J. Hoxie's tests are very interesting and show what high resistances ordinary copper plate grounds may occasionally give. They hardly represent average conditions, but show rather an abnormally low conductivity of the soil in which they were placed.

Since presenting my paper, a large number of gas pipes, treated in different manners, have been located in different places and are being regularly tested; these show about the same magnitude of resistance, some even a much lower resistance than the grounds recorded in my paper.

It undoubtedly is necessary, when using a gas pipe or copper plate as ground, to test it first, before relying on it; and a very convenient way is to put down two pipes at some distance from each other and test them against each other. Connected in multiple for use, the resultant resistance is one-quarter or less of the sum of their resistances, as given by the test.

A good location for grounding pipes is on a lawn, and it may even be advisable to plant a lawn around the pipes, since the keeping of the grass green by watering insures moisture to maintain the conductivity of the ground, and so gives an indication of their operativeness.

DISCUSSION ON "HIGH-TENSION TRANSMISSION" AT NIAGARA FALLS, N.Y., JUNE 26, 1907.

Ralph D. Mershon (by letter): Replying to the points raised by Mr. Rushmore. Whether or not service from a single line is justified, depends upon the value and importance of the customer. One would be justified in going to the expense of two lines for a large and important customer, but such expense would render the business of a small customer unprofitable. Mr. Rushmore raises the question of the grounded wire. I have never been fully convinced that the grounded wire actually affords an appreciable amount of protection against lightning, or, at any rate, an amount of protection which would justify the expense of installing it. I had hoped that Mr. Rowe would, in his paper, bring more convincing proof of the value of the grounded wire than has been submitted in the past by those defending it, but I must say I cannot see that he has done this. The question of two-circuit towers vs. single-circuit towers is one on which many arguments can be advanced on both sides. In the end, the choice must be largely decided by the conditions to be met. In our case it seemed best, for a variety of reasons, to make use of the single-circuit towers. What Mr. Rushmore says in regard to wooden pole-line construction is true in many cases; it is not true in this case however. Where the A-frames were installed, the amount of space available was not sufficient to allow of tower construction, and steel-pole construction would not only have been more expensive than wooden poles, from every standpoint, but the necessary deliveries of steel poles could not have been obtained.

As regards Mr. Finney's tie, I would say that the tie we used was adopted for the reasons set forth in the paper, and only after an exhaustive series of tests on all the ties we knew of or could devise. If Mr. Finney will make actual pulling tests on his tie with aluminum cable and aluminum tie wire, he will find, I think, that it will not fulfil the conditions which, as explained in the paper, it was desired to meet, and which the tie adopted does meet.

DISCUSSION ON "CONSTANTS OF CABLES AND MAGNETIC CONDUCTORS", AT SCHENECTADY, APRIL 25, 1907 (see p. 555)

W. A. Del Mar (by letter): Mr. Berg may well be surprised to find the great number of different formulas devised to express the inductance of a pair of parallel wires. The variety of formulas is remarkable, considering that a simple and accurate formula has been available in most of the standard mathematical treatises on electricity from Clerk Maxwell to Alex. Russel.

The inductance of a circuit is a measure of the magnetic energy associated with the current in it and is defined by the following well-known equation:

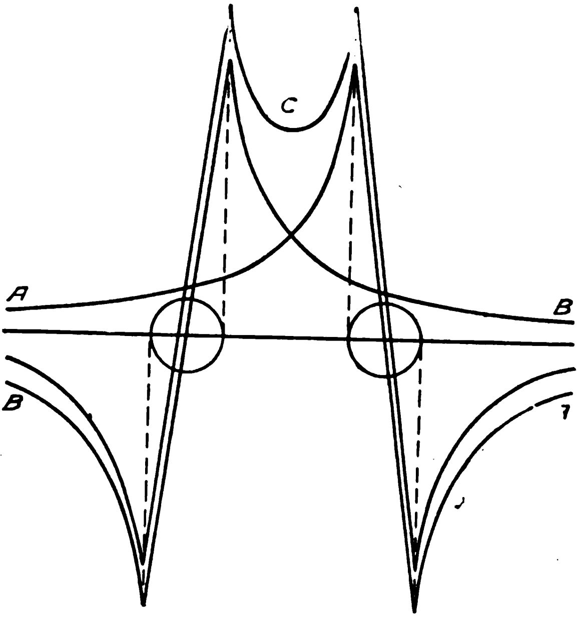


FIG. 1

$$E = \frac{1}{2} L i^2$$

where E = energy in magnetic field interlinked with a circuit of inductance L carrying an unvarying current i. In the case of a circuit composed of two parallel wires, the size of which is negligible in comparison with their distance apart, the inductance is approximately equal to the total flux embraced by the circuit due to unit current therein.

In the paper under discussion this approximation is used as the basis of a formula which is apparently intended to be exact.

By a curious the coincidence, the exact formula is of the form given by Mr. Berg as an approximation; that is, it contains a term $\log \frac{2D}{d}$ instead of $\log \frac{D-r}{r}$ as given in the formula referred to above. Even using the approximation as a basis, the deductions given are not correct, owing to an error in the selection of the limits of integration.

When two conductors carrying currents in opposite directions are brought into proximity, the magnetic whirls around the conductors are squeezed together and the axes of the two whirls are pushed away from the axes of the conductors. In order to include the entire flux, the integration should, therefore, have been extended to the axes of the whirls, instead of merely between the axes of the two wires.

This is shown graphically in Fig. 1 in which the ordinates of the curves *A A* and *B B* represent the flux density around a pair of parallel wires, and the ordinates of the curve *C* show the resultant flux density due to the fields of the two wires. It will be noted that the curve of resultant flux density crosses the horizontal axis outside the axes of the wires, and the inductance will be the entire area between the resultant curve and the horizontal axis. The area of this curve expressed as a formula is cumbersome in the extreme and withal useless, because as stated above it is based on incorrect premises.

The equation defining inductance is stated above in terms of an unvarying current because the flux due to a varying current is not distributed in a condition of equilibrium, and is therefore not a definite quantity but depends upon the rate of the variation of the current. The flux due to unit current varying at any particular rate may be called the "effective inductance" at that rate.

A paper to be presented at the annual meeting of the American Institute of Electrical Engineers, New York, May 19, 1908.

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(Subject to final revision for the Transactions.)

COMPARATIVE TESTS OF LIGHTNING PROTECTION DEVICES ON THE TAYLORS FALLS TRANSMISSION SYSTEM

BY J. F. VAUGHAN

Recent Institute discussions have brought out a decided difference of opinion on the value of certain lightning protective devices and have expressed a demand for positive data on line protection especially. This paper furnishes data obtained last summer on an operating line experimentally equipped with various protective devices. The results are of especial interest in being actual records made by means of tell-tale papers applied not only to the station protective devices but also to those on the line, and even to the line insulators themselves throughout the system.

When the transmission from Taylor's Falls to Minneapolis, Minnesota, was built in 1905, local conditions demanded the best lightning protection available. The line ran southwest from the power house a distance of about 40 miles through a rolling country, partly wooded and full of lakes and swamps. It lay in the natural path of thunderstorms forming to the northwest of Minneapolis. Investigation indicated a zone about 9 miles long near the middle of the line that was especially subject to severe lightning, and the splintering of six poles in different parts of this zone before any wire was strung suggested the necessity for special protection at exposed points against direct stroke.

On account of the wide divergence of opinion on the subject of lightning protection, and the impossibility of reconciling the conflicting results of practice, it was decided to try out on the Taylors Falls System all existing devices of promise and such others as might be devised, in order, by comparing them in actual service, to work out some effective scheme for future protection.

Description of system. Current is generated by four 2500-kw., 2300-volt, 60-cycle, three-phase water-wheel driven machines, each operated as a unit, with a bank of three 900 kw. transformers connected delta-delta and stepping up to 50,000 volts. The pressure is stepped down at the main sub-station on the outskirts of Minneapolis to 13,800 volts for local distribution and transmission to a steam and water power local plant

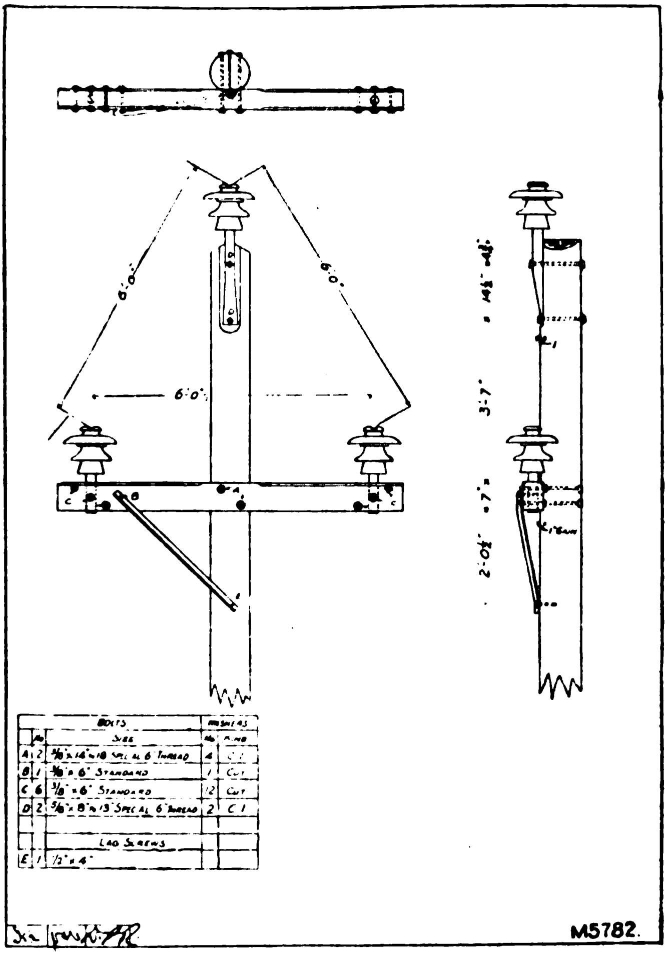
6'-0"
6'-0"
6'-0"
3'-7"
7"
2'-0½"
A
B
C
C
BOLTS
WASHERS
No.
SIZE
No.
KIND
A 2 ⅝" x 14" x 18" Special 6" Thread 4 C I
B 1 ⅝" x 6" Standard 1 Cut
C 6 ⅜" x 6" Standard 12 Cut
D 2 ⅝" x 8" x 13" Special 6" Thread 2 C I
LAG SCREWS
E 1 ½" x 4"
M5782.

Fig. 1

in the city. Automatic time-limit relay oil switches control the lines and transformers at all three plants.

The transmission consists of a single line built on private right-of-way using Idaho cedar poles of 45 ft. standard length,

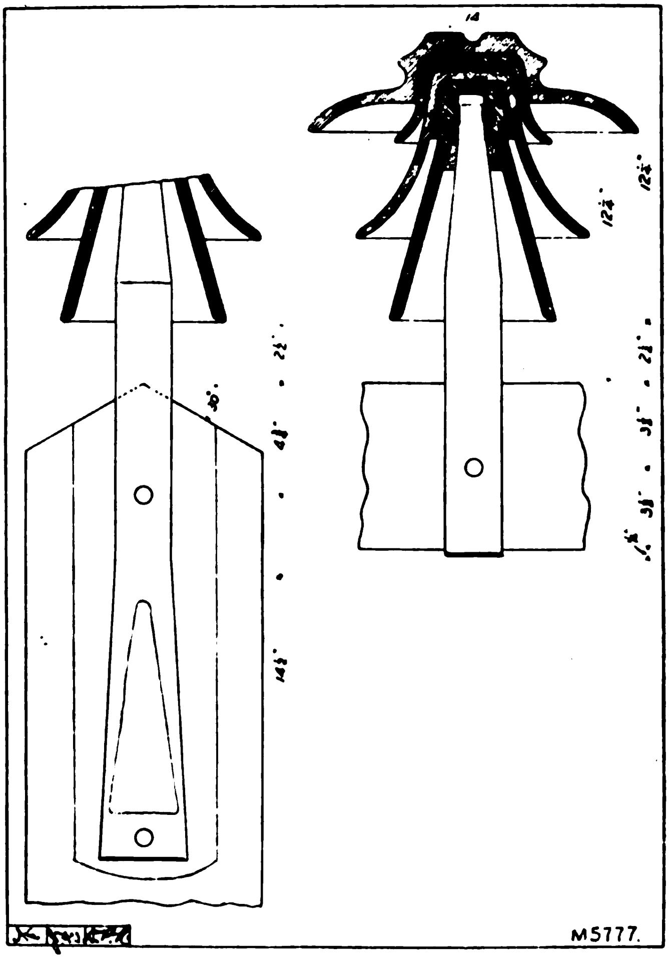

Fig. 2

carrying three 0000 semi-hard-drawn copper cables supported on 14 in. four-part porcelain insulators arranged on a 6-ft. equilateral triangle with the apex at the pole-top (Fig. 1). The insulators (Figs. 2 and 3) were originally selected from a number of samples, including five others of the writer's design,

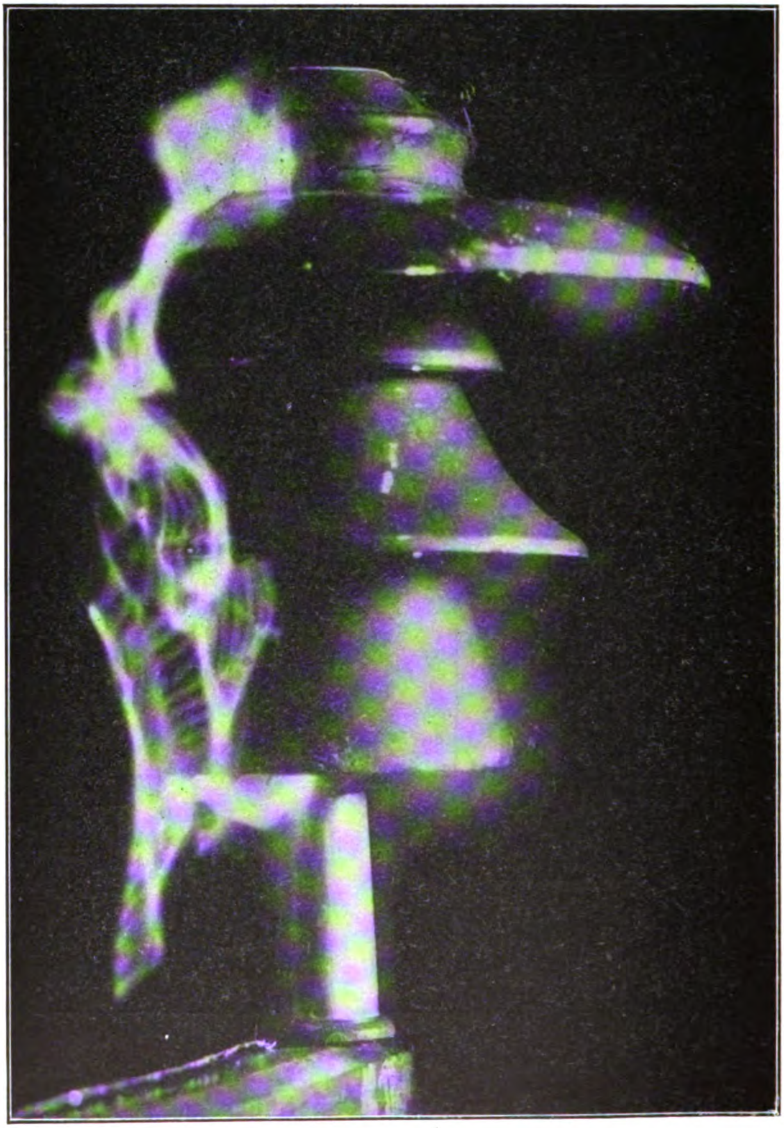

FIG. 3--Photograph of insulator flash-over, under artificial rain test as the only insulator obtainable which, under driving rain test, showed properly distributed electrostatic stress without concentration on any one part. These had already proved unusually rugged, as shown by two years' use, without any electrical failures on 75 miles of 57,000-volt transmission on the Puyallup system in the state of Washington. The insulators are supported on iron-pipe pins cemented into them and bolted to the pole-tops or set into the cross-arms. The line also carries a pair of telephone wires on an arm 7.5 ft. below the transmission arm.

The telephone system consists of a metallic circuit of No. 10 copper mounted on porcelain insulators of the same design as the ordinary double petticoat glass type. Instruments are permanently connected at the power house, sub-station, and inspector's cottage at the middle of the line, and booths provided at various points for tapping in inspectors' portable instruments.

Station protection. For protection of the power house and sub-station low-equivalent multigap arresters and oil-insulated choke-coils were installed, supplemented at the sub-station by a set of experimental aluminum cell-type arresters connected to the entering line through a small number of arrester gaps in zigzag arrangement, set so as to be normally active.

The transformers at all stations were further protected on their low-tension sides by static discharge gaps.

LINE PROTECTION.

Horn-type arrester. Three types were installed, one at each end and one in the middle of the line, primarily to pass off disturbances of unusual magnitude, and also to experiment with the different forms.

The sub-station arrester consisted of a single gap on each phase, arranged with a sheaf of water jets forming series resistance to ground. This required too much water and was replaced by tanks of water with terminals of carbon rods in fiber tubes (Fig. 4).

The power house arrester had two gaps in series between each phase and ground, with the second gap shunted by carbon terminals placed in the river (Fig. 5).

The Hugo arrester, at the middle of the line, was built on the selective resistance principle, with three gaps in series on each leg, the second and third gaps being shunted by water-box resistances (Fig. 6).

Overheaded grounded wires. Four types were erected in the nine-mile zone in 0.5 mile lengths, alternating with 0.5 mile lengths of unprotected line as follows:

Type *A*. Two wires mounted on a cross-arm 5 ft. apart on either side of the top line wire and about 18 in. below it (Fig. 12).

Type *B*. Two wires supported on standards of 1.25 in. iron pipe 6 ft. apart and 18 in. above the top line wire (Fig. 7).

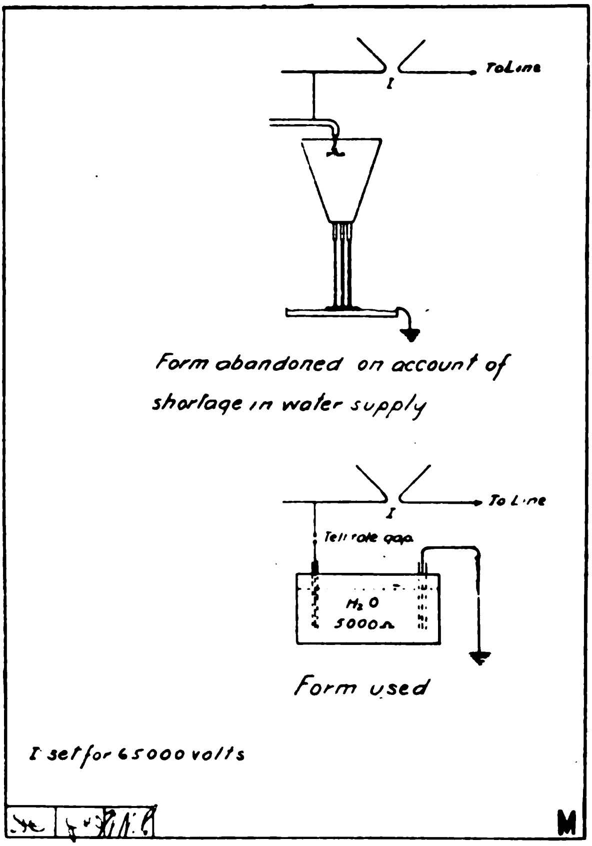

FIG. 4

Type *C*. One wire on knobs attached to the pole near the center of the delta (Fig. 12).

Type *D*. Two wires in the same position as in Type *B*, but supported on pipe pins set in the ends of a cross-arm attached near the top of the pole.

In the above constructions the grounded wires were of No. 6

hard-drawn copper. The ground connections were of 0.5 in. by 0.0625 in. galvanized iron ribbon wire at every fourth pole and the ground made by 0.75 in. galvanized iron pipe driven to moist ground.

Lightning-rods. Four types were used, erected in the nine-mile zone in sections from one to two miles long, separated by unprotected sections as in the case of the grounded wire constructions as follows:

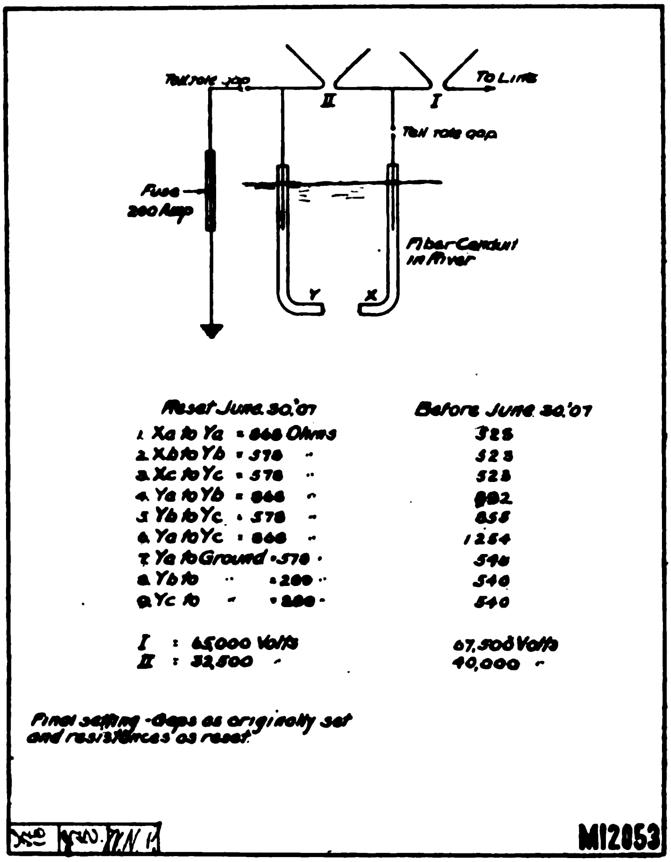

FIG. 5

Type *A*. Rods of 1.25 in. galvanized iron pipe attached to the poles and extended by tridents of copper wire reaching 6 ft. above the top line wire (Fig. 7).

Type *B*. Rods of 1.5 in. galvanized iron pipe mounted on separate poles 20 ft. to one side of the transmission line and topped by tridents of copper wire extending 25 ft. above the top line wire. Rod poles were spaced at the centers of alternate spans (Fig. 7).

Type *C*. Same as Type *B*, but spaced three rods to four spans.

Type *D*. Same as Type *B*, but spaced 1000 ft. apart.

Ground connections were made as on grounded wire construction, but with two grounds for each rod pole, one at the base of the pole and the other 20 ft. or more away, to insure especially wet ground and to increase the discharge area.

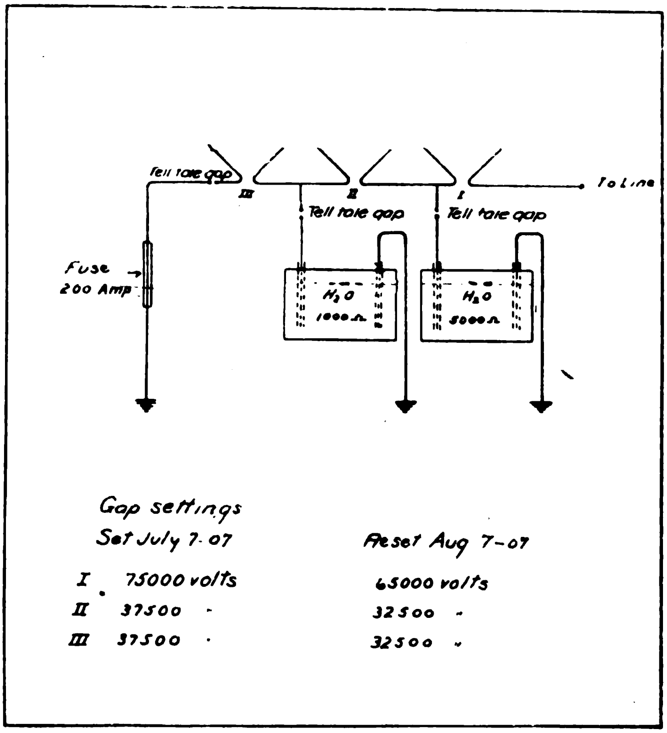

FIG. 6

Telephone protection. Each permanent and temporary telephone connection was made through a one-to-one repeating coil and discharge gaps to ground set to break down at about 900 volts.*

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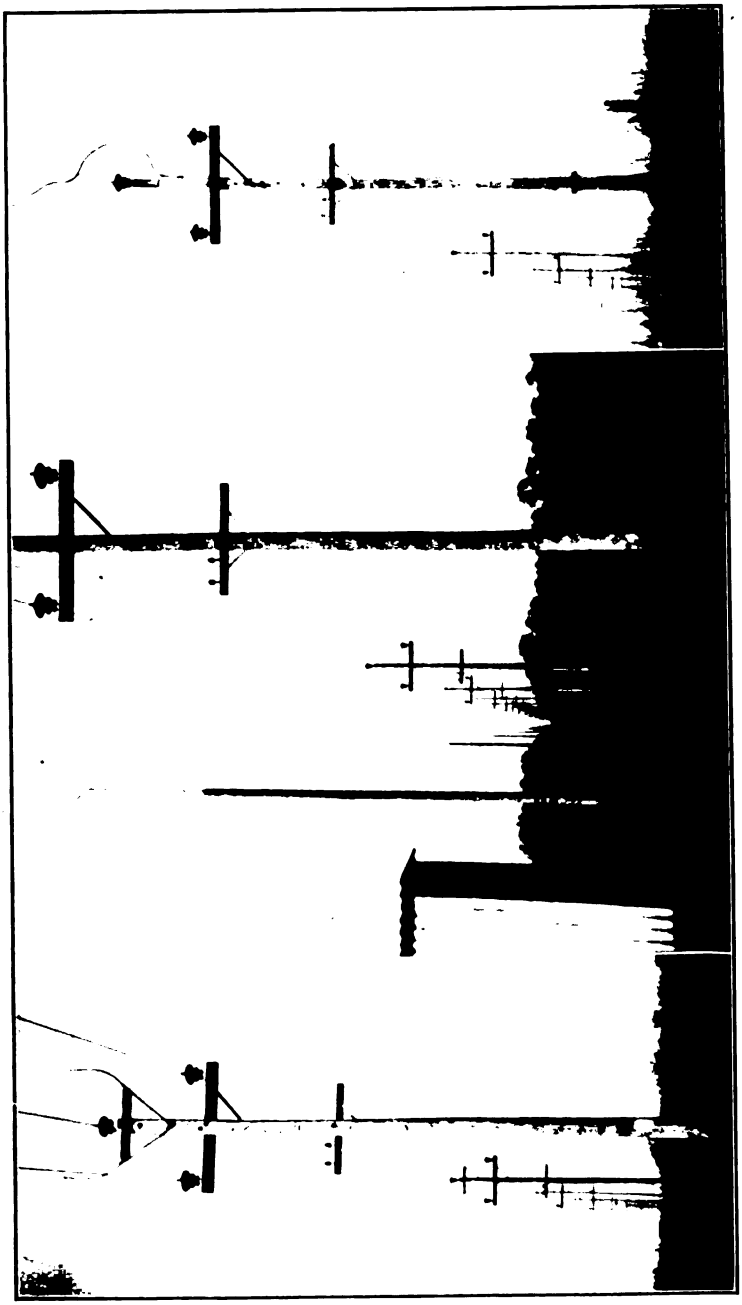
* (American Tel. & Tel. Co. Protection 74-A.)



Overhead grounded wire—type "B"

Lightning-rod—type "B"

Lightning-rod—type "A"

FIG. 7

Recording devices. All station arresters were provided with tell-tale papers. To determine the character of disturbances, their extent, magnitude, and effect on line and apparatus, ground connections of all protective devices were provided with gaps for the insertion of tell-tale papers.

To study the stresses on the line insulation throughout its length and the behavior of the insulators, each insulator pin at every third pole was grounded through a separate ground wire and tell-tale box (Fig. 7), supplemented by choke-coils shunted with tell-tale gaps cut into the line wires at various points.

After a number of insulators on grounded pins had been damaged, the pin grounds were removed from four sections of about one mile long each, separated by one-mile sections left grounded, to prove whether the grounding was in any way responsible for insulator failures.

Records. The following records were kept:

A. Weather conditions shown by United States Weather Bureau reports, and reports of observers along the line.

B. Storm occurrences and data furnished by local men in charge.

C. Operating and special reports of interruptions to service and damage to system.

D. Tell-tale papers collected after each storm.

E. Graphic analysis of tell-tale papers for each storm.

Operation and results of first season. The transmission system was started up in December, 1906, and lightning protection records carried through the following summer. The lightning season opened late in March and lasted into October. Thirty-two storms occurred during this season within reach of the line.

The following tabulation gives data on the storms and damage to system, or interruptions to service.

The tabulation shows that in 17 out of the 32 storms the service was interrupted and 8 of these storms caused damage to insulators, while only one storm affected the station apparatus; this was due probably to a defect in a transformer bushing, but was not sufficient to interrupt the service. Out of 42 insulators damaged, only 3 were punctured, the rest being shattered.

The plan and profile of the line (Fig. 8) show the distribution of damaged insulators on the line and indicate their phases, location on pole or tower, etc.

The following tabulation further analyses insulator damage.

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ANALYSIS OF INSULATOR FAILURES

Total number of storms	32				
Number damaging insulators	8				
Total number of insulators on line, approximately	5,500				
Number damaged	42	0.8%	of	total	damaged
“ shattered	39	92.9%	“	“	“
“ punctured	3	7.1%	“	“	“
“ top insulators	23	54.7%	“	“	“
“ on west side	6	14.3%	“	“	“
“ “ east “	13	31.0%	“	“	“
“ “ brace “	12	28.6%	“	“	“
“ “ opposite side	5	11.9%	“	“	“
Total number insulators on grounded pins, approx	1,650	30.0%	“	“	
Total number insulators on ungrounded pins, approx	3,850	70.0%	“	“	
Number damaged on grounded pins and towers	35	83.3%	“	“	damaged
Number damaged on towers	3	7.2%	“	“	“
“ “ on ungrounded pins.	7	16.7%	“	“	“
“ “ in sections where grounds had been removed	4	9.5%	“	“	“
“ “ on more or less exposed heights	28	66.7%	“	“	“
“ “ in wet bottoms	8	19.0%	“	“	“
“ “ scattering	6	14.3%	“	“	“
Number damaged under overhead grounded wires. (At or near ends only)	2	4.8%	“	“	“
Number damaged under lightning rods on poles	3	7.2%	“	“	“
“ “ under lightning rods on separate poles.	0	0.0%	“	“	“
Poles split.					
Number with pin grounds	0				
Number without pin grounds	1				
Poles burned.					
Number with pin grounds	2				
Number without pin grounds	0				

The chief operating troubles were interruptions due to short-circuits and grounds from spilling over of insulators, generally accompanied by permanent damage to a part of such insulators (Figs. 9 and 10). Another serious cause of interruption during the latter part of the season was due to too low a setting of the horn arrester at the power house; this did not appear with the higher setting earlier in the season.

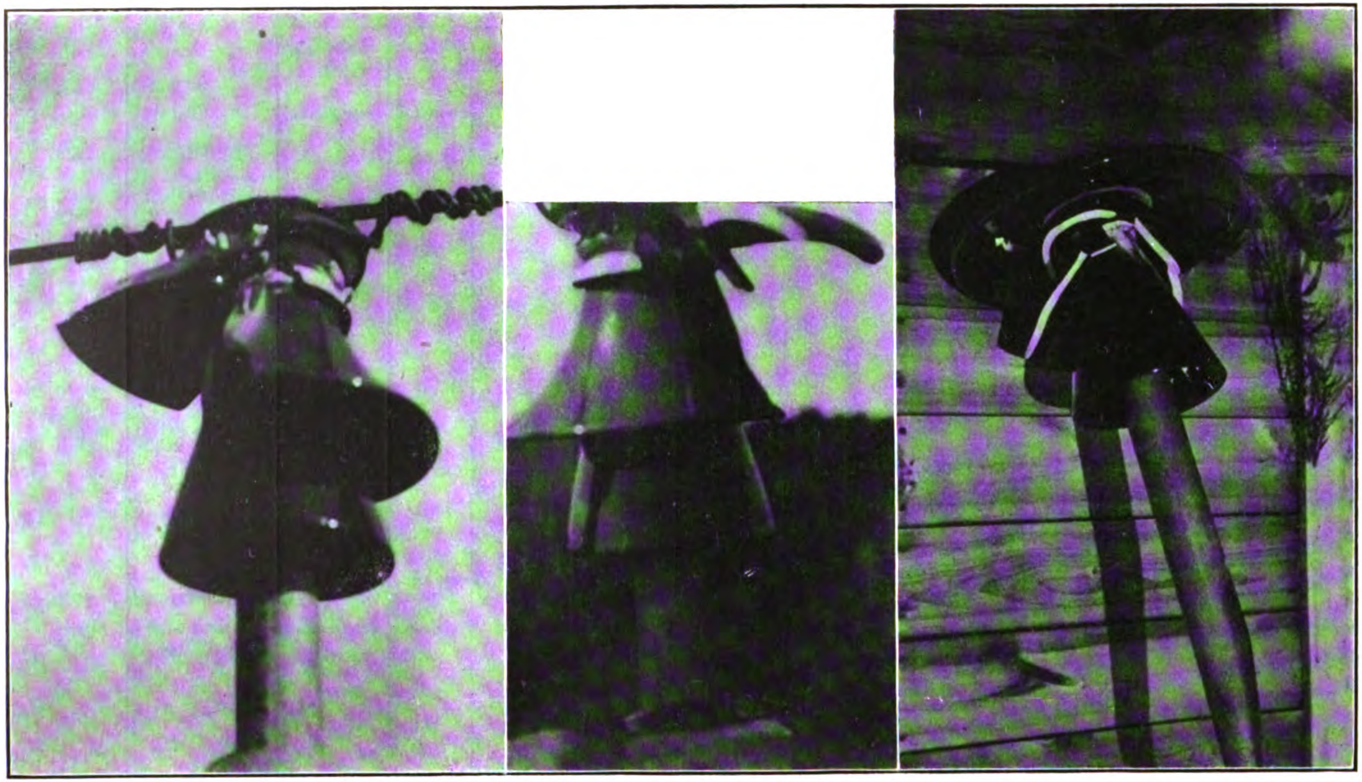
DATA ON STORMS AND DAMAGE TO SYSTEM

Characteristics of Storms.												Damage.		
Date	Time	Location	Direction	Lightning	In. of rain	Wind Max. m.p.h.	Pole No.	Ph.	Loc.	Pin	Brace	Insulation damage	Duration of interruptions	Remarks
3/23	11:20–11:50 a.m	Dist.		Little	0.03	24								
5/12–13	9 p.m.–6 a.m.	"		Heavy	0.10	32	1532	C	Top	Gr.	—	*	None	Sub-A transformer bushing punctured. Telephone not disturbed.
6/9	3–6 a.m.	Near sub-A		"	0.10	40							"	
6/9	5 p.m.			1-flash	1.20	—							"	
6/15	8–10 a.m.			Frequent	0.30	44							"	
6/16	5 p.m.	Dist. to NW			T	32							"	
6/21	5:30–8:30 p.m.		W. to E.	Heavy	0.55	27							"	
6/22–3	9:30 p.m.–1 a.m.			"	0.16	30	1571	A	W-side	Gr.	Br.	*	18 hrs.	Pole 1571 burned by wire, dropping from broken insulator. Line interrupted by switching following trouble.
6/23	12–1 p.m.			Mild	0.0								None	
6/24	5-p.m.	Dist. to E.			0.0	16							"	
6/29	6 a.m.			Heavy	0.0	17	1474	B	W-side	Gr.	None	*	"	Insulators replaced Sunday, July 1, when line shut down for repairs.
							1478	"	E- "	"	Br.	*		
6/30	12–8 a.m.	5 mi. from p.h. bet. poles 172–288.		"	0.03	23	193	A	Top	"	None	*	Line held for 1 hour after damage; then out 30 hours for repairs.	
							Tr 224	"	"	"	—	*		
							267	"	"	"	—	*		
							Tr 288	"	"	"	—	*		
							193	B	W-side	"	—	*		
							172	C	E-side	"	Br.	*		
							208	"	" - "	"	"	*		
							Tr 224	"	" - "	"	"	*		
7/4	10:30–12:30 p.m.	2 mi. east of Hugo.	W. to E.	Heavy	0.16	38	918	A	E- "	"	"	*		Power not on line during day.
							934	"	Top	"	—	*		
							937	"	"	"	—	*		
							909	B	"	"	—	*		
							912	"	"	"	—	*		
							915	"	"	"	—	*		
							918	C	W-side	"	None	*		Pole 918 burned by lightning.
							931	"	E- "	"	Br.	*		
7/13	9:30–11 p.m.			Heavy	0.36	53								
7/14–15	8:30 p.m.–1 a.m.	Near p.h.		"	2.76	20	60	B	Top	"	—	*	12 hrs.	Telephone not disturbed.
							72	"	"	"	—	*		
7/19	1 a.m.	Dist. to E.			0.36	20								
8/1	1:30–2 a.m.	Dist. to W.			0.22	46								
8/4	5:30–7.30 p.m.	Dist.			1.39	27								
8/6	2 a.m.	Dist.			0.0	21								

Date	time	Location	Direction	Lightning	In. of rain	Wind max. m.p.h.	Pole	Ph.	Loc.	Pin	Brace.	Insulation damage	Duration of interruption	Remarks.
8/6	1:30-3 p.m.			Heavy	0.04		1028	A	Top	Gr.	—	★	25 hrs.	
							1065	"	"	Not	—	✱		Lightningrodonpole
							1067	"	"	Gr.	—	✱		" " " "
							1070	"	"	"	—	✱		" " " "
							1150	B	E-side	"	Br.	✱		
							1111	C	Top	"	—	✱		
							1135	"	"	"	—	✱		
							1138	"	"	"	—	✱		
							1141	"	"	"	—	✱		
							1144	"	"	"	—	✱		
8/8	12:30-1:30 a.m.	Dist.			0.16	24							None	
8/15	6:30-8 p.m.	Minneapolis to p.h.	Parallel to line	Heavy	0.76	40							"	Heavy line disturbances.
8/18	7:30-12 p.m.	Minneapolis to p.h.	Parallel to line	Very hvy.	2.26	62	1332	A	E-side	Gr.	Br.	✱	20 hrs.	
							1335	"	"	"	"	✱		
							1341	"	" "	"	"	✱		
							1355	"	Top	Not	—	✱		
							1357	"	"	"	—	✱		Pole split.
							1351	B	W-side	"	Br.	✱		
							1357	"	" "	"	None	✱		
							1350	C	E-side	"	Br.	✱		
							1351	"	" "	"	None	✱		
							1387	"	" "	Gr.	—	✱		
9/6	7:30-9 p.m.	E. of Minn.		Heavy	0.16	25							None	
9/15	4:30-5 p.m. and 7-8 p.m.			"	0.32	19							P. h. breaker opened by horns	Between Sept. 15 and 23 breakers at p.h. opened 9 times by operation of p.h. horn arresters which were set at too low a discharge point.
9/16	1:30-2 a.m.			"	0.38	25								
9/17	3:30-4:30 a.m.				0.22	38							P.h. breaker opened; no horn discharge.	
9/18	4-5:30-p.m.				0.01	36								
9/19	8 p.m. all night				2.98	38							P.h. breaker opened twice by horn.	
9/22	6:30-7:30 p.m.				0.05	28							P.h. breaker opened by horn	
9/23	5:30 p.m.	No storm.											P.h. breaker opened by horn.	
9/24	1:45 a.m.	" "											12 hrs.	Line choke coil grounded.
10/1	12 m.	Dist. Ltg.			0.63	27								
10/3	4-a.m.	" "			0.15	27								

Abbreviations and Symbols.

Ph. = Phase A, B, or C.
Loc = Location on pole.
Br. = Brace side.
P.h. = Power house.
None = Not brace side.
Gr. or Not = Insulator pin grounded or not.
✱ = Insulator shattered.
★ = Insulator punctured.



Punctured 8/2/06 in line test,
tower 1563

Punctured 8/2/06 in line test,
tower 1564

Punctured 8/2/06 in line test,
tower pole 1451

FIG. 9--Damaged insulators

Graphic records of tell-tale papers. The graphic records of tell-tale papers show in the form of curves (Figs. 11 and 12 and Appendix) the relative stresses on and discharges over insulators, or through arresters throughout the system, for the full storm series of the season comparing the action of various protective devices storm by storm.

The ordinates of the curves represent the relative size of puncture of tell-tale papers, the scale being so selected as to show as nearly as practicable the relative activity at each point on the line. Curves *A*, *B*, and *C* (Fig. 11) refer to the tell-tale papers placed in the grounds of the insulator pins on the corresponding phases and the fourth curve "Sp." to the papers in the grounds of the protective devices. The relation of phases and transposition points, locations of special protective devices, choke-coils, pole numbers, etc., are shown at the top of the sheet. The columns to the right refer to the papers in the various types of arresters and give data for each storm. The curves on enlarged chart (Fig. 12) show the sum of the diameters of punctures for the three phases, and the corresponding punctures for the protective device grounds. In the preparation of these charts the tell-tale papers have been interpreted as follows:

Puncture, honeycombing, or discoloration of tell-tale papers, without blistering indicates quiet static discharge or static stress, as from the condenser action of the line and insulators, shown on chart by light line in curves *A*, *B*, and *C* (Fig. 11) and by "*S*" on the arrester records.

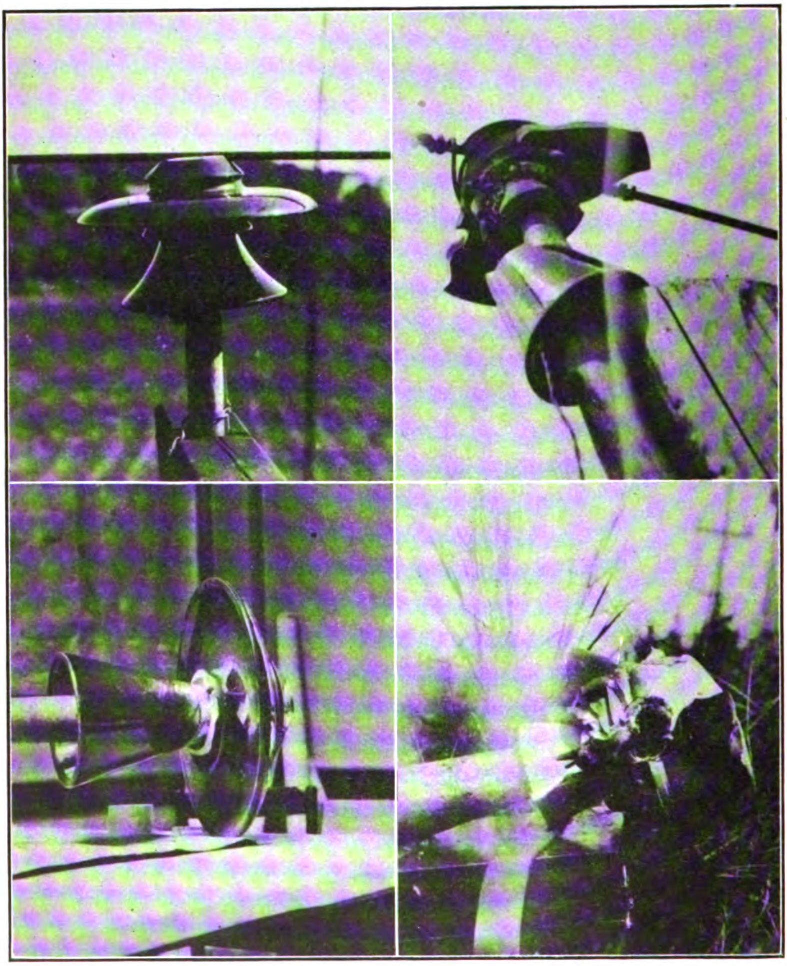
Blistering, that is, bursting apart of laminations of tell-tale papers or tearing of papers, without burning, indicates a disruptive static discharge, shown by heavy line in curves and "*O*" (Fig. 11).

Burning of puncture indicates dynamic current, shown by solid curve and "*O*" (Fig. 11).

DATA FROM OPERATING REPORTS OF 1907.

Storm, May 12–13, 9 *p.m. to* 6 *a.m.* Sub-station transformer bushing grounded. Telephone wires at sub-station burned off. Top insulator pole 1532 Ph. "*C*", 4.5 miles from sub-station shattered, one side of all petticoats being broken. Current leaking to grounded pin slowly burning pole. No interruption until current off for repairs 19 hours later.

Storm, June 22–23, 9:30 *p.m. to* 1 *a.m.* Pole 1571 reported burning at 11 p.m. 11:30 to 12 p.m. surges on power house instruments and heavy discharges over static dischargers on low-tension side of transformers, burning out one set of dischargers. Breakers thrown out, then line cleared up. Pole 1571 reported still burning at 12:30, grounded line. Double arms burned off by wire dropping from broken insulator. Pin ground wire across line and telephone wires, making the telephone alive.



Shattered 8/18/07, pole 1341 Punctured 8/7/07, pole 1028
Punctured 6/29/07, pole 1474 Same insulator (pole 1028)
FIG. 10 showing fused puncture

Pole badly burned, necessitating renewal. Telephone in order after clearing wires. When spillover at pole 1571 Ph. "*A*", pin ground fused off. Sub-station cell-type arrester active on Ph. "B" and "C". Low-equivalent arrester inactive. Service interrupted by switching operations after trouble only. Line out for repairs 18 hours.

Storm, June 29, 12 *to* 6 *a.m.* Side insulators poles 1474 and 1478 "B" punctured and broken. No interruption until repairs June 30. Telephone out. Station arresters inactive.

Storm, June 30, 12 to 8 *a.m.* Top insulators shattered on towers 224, 288, and poles 193 and 267 Ph. "A"; pole 193 Ph. "B"; and tower 224 and poles 172 and 208 Ph. "C"; P.H. horn arrester discharged on Ph. "B", arc breaking in two to three seconds without any disturbance to synchronous apparatus. Short-circuit one hour later.

Storm, July 4, 10:30 *a.m. to* 12:30 *p.m.* Current not on line after 4 a.m. Insulators shattered on poles 918, 934, 937, Ph. "A"; 909, 912, 915 Ph. "B"; and 918, 931 Ph. "C". Pole 918 burned off two feet below cross-arm. Pole set on fire by lightning as no line current was on. Line tested and found short-circuited at 1 p.m. Line put in operation 7:25 a.m. July 5. Most of damage on unprotected section between overhead ground wires types "A" and "B".

Storm, July 14–15, 8:30 *p.m. to* 1 *a.m.* Near power house. Insulators shattered on poles 60 and 72 Ph. "B" shutting down station for 12 hrs. Power house static dischargers burned somewhat. Power house horn arrester operated once. Telephone not affected.

Storm, Aug. 6, 1:30 *to* 3 *p.m.* Nine insulators shattered on poles 1065, 1067, 1070 Ph. "A"; 1150, Ph. "B", 1111, 1135, 1138, 1141, 1144, Ph. "C". Insulator punctured pole 1028, Ph. "A". Fused through all four parts and several minor punctures. Hugo horn arrester slightly active Ph. "A"; others inactive. Cell-type arrester discharged Ph. "A" and "B". Sub-station low-equivalent arresters discharged Ph. "C". Line out 25 hours.

Storm, August 18, 7:30 *to* 12 *p.m.* Most severe storm for several years. Lightning practically incessant. Heavy short-circuit on line at 8 p.m.; recovered for few minutes, then permanently out. Pole 1357, from which ground wires had been removed, split from top to below cross-arm where guy was attached. Top insulator shattered. Nine other insulators shattered on poles 1332, 1335, 1341, 1355, 1357, Ph. " A "; 1350, 1351, 1357, Ph. " B "; and 1351, 1387, Ph. " C ". Six of these were in sections where pin grounds had been removed. No evidence of short-circuits on any poles. Papers in line choke-coils on pole 1356 burned up and cylinders burned. Choke coil on 1615 Ph. " A " paper blistered. Beside spillovers between 1300 and 1400, several between 800 and 950, but without damage. Other spillovers on 300, 353, 408, 563, 1034, and 1254 without damage.

Storms, September 15–42. Several of these were severe. Transmission line put out of service 9 times in 9 days. Six of these caused by power house horn arrester discharging, opening breakers. Arc held on horn tips, and in one case followed up lead toward tower, drawing an arc 20 to 30 ft. long. Probable cause, wind. Action of horns much more severe than with wider setting during earlier part of season. No damage from lightning.

ANALYSIS OF RECORDS

Examination of the plan and profile (Fig. 8) indicates that:

Points where the line was especially liable to damage are, first, exposed heights and, next, wet bottom lands.

Damage was usually concentrated within a distance of a mile or two, with the exception of the two storms of June 30 and August 6, in the latter of which the storm crossed the line at a slight angle; and in the former, although there is no record of the direction of travel of the storm, there are indications that it traveled along the line for some distance.

Thus far, trouble has not been confined to any defined points on the line, but as yet there is insufficient conclusive evidence on this point.

The tabulation of line failures appears to show that:

Where grounded and ungrounded pins come on adjacent poles, damage to the insulators generally occurred at the grounded pin, but the damage of a group of insulators on a section of line where all grounds had been removed and on pole 1065 indicates that grounding the pins probably did not materially increase the danger of damage.

Top insulators are somewhat more liable to damage than those on the sides and those on the brace side are apparently somewhat more affected than those on the opposite side.

Overhead grounded wire construction materially protects

insulators. The lightning-rods do not seem to have much effect except in cases of direct stroke.

The one case of pole splitting was a pole with no ground connection.

Examination of the tell-tale papers and graphic charts (Appendix and Fig. 11) indicates that:

Storms follow no well-defined paths, nor are their effects confined to any particular part of the line.

Stresses do not occur at any definite points.

Principal disturbances are due to immense static charges on the line in the immediate vicinity of storms. These charges are of great intensity and concentration, frequently spilling over a number of insulators without traveling along the line more than a few hundred feet.

The disturbances are confined to areas extending from one-half to two miles along the line, excepting where storms are traveling parallel to the line, as in the storm of August 18, which suggests recurrent and decreasing activity as the storm passes down the line. Even in this case no area of disturbance was over three miles in length.

In general, the protected nine-mile zone shows an appreciable decrease of insulator stress and activity of devices for distance storms and a very decided shielding effect of overhead grounded wires as well.

By following the curves for each type of grounded wire down through the season on the large graphic chart, Fig. 11, the activity of the grounded wires and the corresponding smoothing out of stresses on the insulators appear pronounced and consistent, with the possible exception of the storm of August 18, which was of unusual severity and traveling parallel to the line, so that charges may have been induced on the unprotected lengths of line between the protected sections of sufficient volume to spread out through the protected sections. A study of the enlarged chart, however, shows pronounced shielding effect even for this storm. The shielding action is especially well shown in the plot for the heavy storm of July 4, which occurred when the line was dead. This storm in traveling parallel to the line from southwest to northeast would naturally affect the unprotected sections of the line between the shielded sections. The chart shows how the shielding effect at the west ends of the short protected sections is counteracted by charges evidently coming on to the unprotected line as the storm approaches each protected section and how it prevents the reestablishment of the charge for some distance into the unprotected sections at the opposite ends.

Although more damage was done to the top and east or brace side insulators, in general the stresses appear greater on the west side, which in this case was toward the approach of the storm.

The effectiveness of the various types of overhead grounded wire appears to be in proportion to their theoretical value, the wires well above the line being the best and the wire in the center of the delta the worst. The activity of the lightning-rods, especially those at the side of the line, is marked. In this same storm, one of type " B " rods passed off a discharge which can be accounted for only by discharge between cloud and ground. This is of especial interest, as a lightning flash photographed by one of the inspectors the previous season showed ramifications apparently covering a territory a mile or two in diameter, emphasizing the necessity for some such protection.* This pole may have received a branch of such a direct stroke and in any case shielded the line from any unusual stress at that point.

The station arrester records on the graphic chart show the low-equivalent type of arresters to have operated according to their theoretical design; but whether the volume discharged was sufficient to keep down dangerous potentials is not certain, since in each important case the simultaneous and vigorous operation of the power house horn arrester outside the station indicated that it took the brunt of the discharge. The cell-type arrester was apparently more sensitive and operated more freely than the other types. There is no record, however, to show its action in disposing of abnormally heavy discharges. On the other hand, it appeared to be more sensitive in responding to strains due to a grounded line, and discharged for considerable periods under this condition without damage. The operation of the horn arresters, especially at the power house has been very promising and appears to fulfil their intended function as an emergency device. Their operation has been chiefly when the line was grounded by the failure of an insulator, but there is one case where the power house horn arrester discharged over both gaps in series without any indication of discharge through the water shunt of the second horn; this indicates that it passed off a high-frequency static discharge without allowing the line current to follow. But this single case is not conclusive. There are other cases, however, which show the passage of heavy disruptive discharges which indicate that these types have handled high-frequency disturbances as well as low-frequency surges. From their action so far it is believed that the two and three-gap types of horn arresters will be effective in handling occasional disturbances whether static or dynamic which might otherwise be of too great magnitude for the station arresters to dissipate, and that this can be done with settings which will not interrupt the line nor necessarily disturb synchronous apparatus.

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* See TRANSACTIONS A. I. E. E., Vol. XXV., p. 901 to 926.

The telephone line ordinarily operated quietly, but, although often too noisy to use in case of line trouble, it was, as a rule, kept from damage by the protectors and recovered when the line cleared up. The effectiveness of the protectors was well illustrated during a ground on one phase by the immediate burning out of two instruments not protected, while a protector on the third instrument discharged freely with no damage to the instrument.

CONCLUSIONS

The results of the Taylors Falls experiments so far indicate that:

The principal trouble is from temporary or permanent breakdown of line insulation by static charges induced in the line by passing storms.

Direct strokes between cloud and ground may occur at any time. Although there were several cases of damage so caused during construction, the first season's operation gives evidence of only one case and that without damage.

The induced charges are highly concentrated, and often of immense volume and intensity, discharging to ground over insulators with a disruptive effect that tends to shatter, but rarely to puncture them, often without line current following. Line current may or may not follow these discharges; if it follows, it may only temporarily ground or short-circuit the line.

Arcs established by insulator spillovers or leakage of charging current through damaged insulators may burn pole structures or further damage insulators and even fuse the line wire.

Such disturbances may occur anwhere on the line, but with a preference for exposed heights and to a less degree to wet lowlands.

There is no evidence of surges other than the direct effects of grounds or short-circuits, and nor of stress at any definite points on the line such as from reflected or standing waves.

Top insulators, and to a less extent those on the cross-arm-brace side of the pole, apparently are more liable to damage, although the cases are not sufficiently frequent to be conclusive.

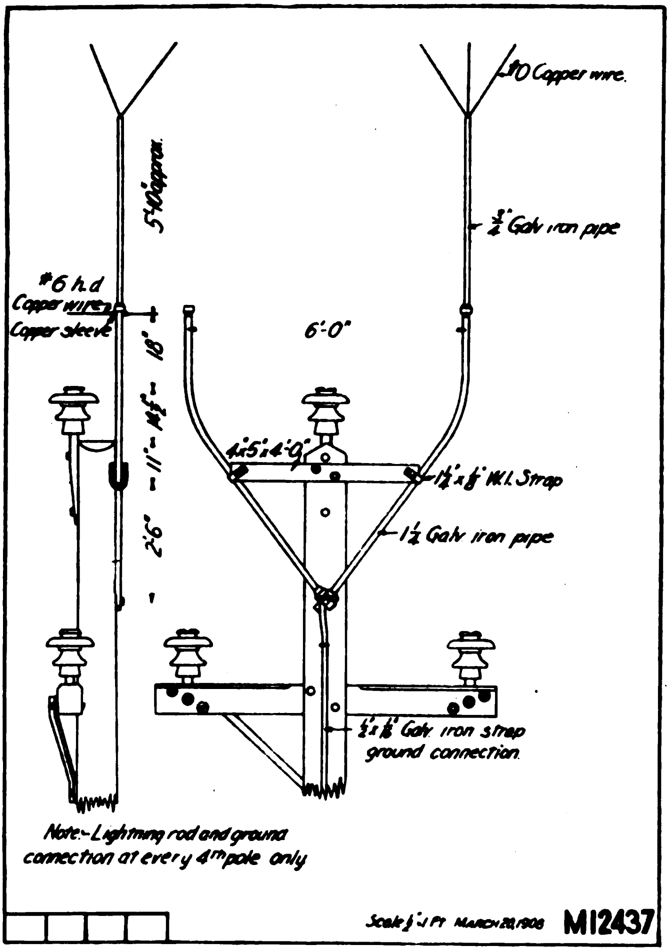
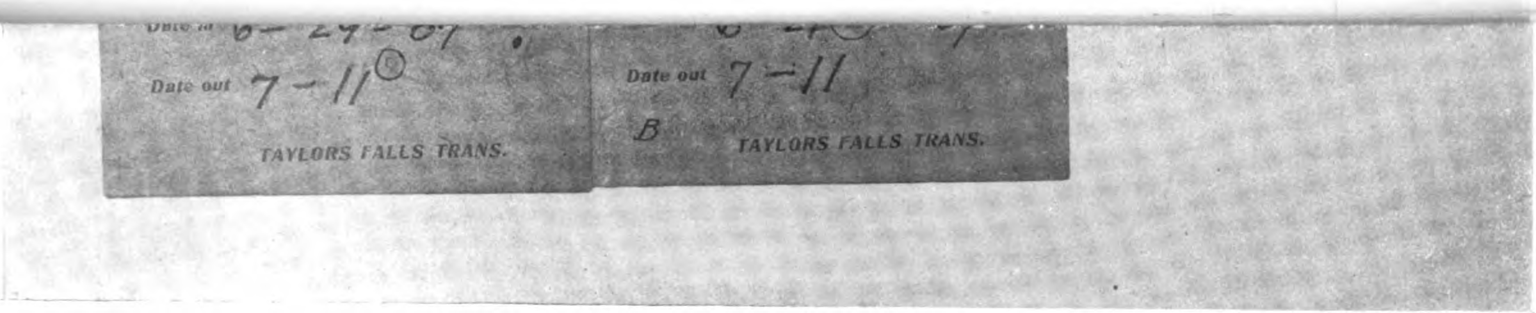


FIG. 13

Grounding of insulator pins by tower structures or otherwise has comparatively little effect in assisting insulator breakdowns.

Overhead grounded wires are of decided value in shielding the



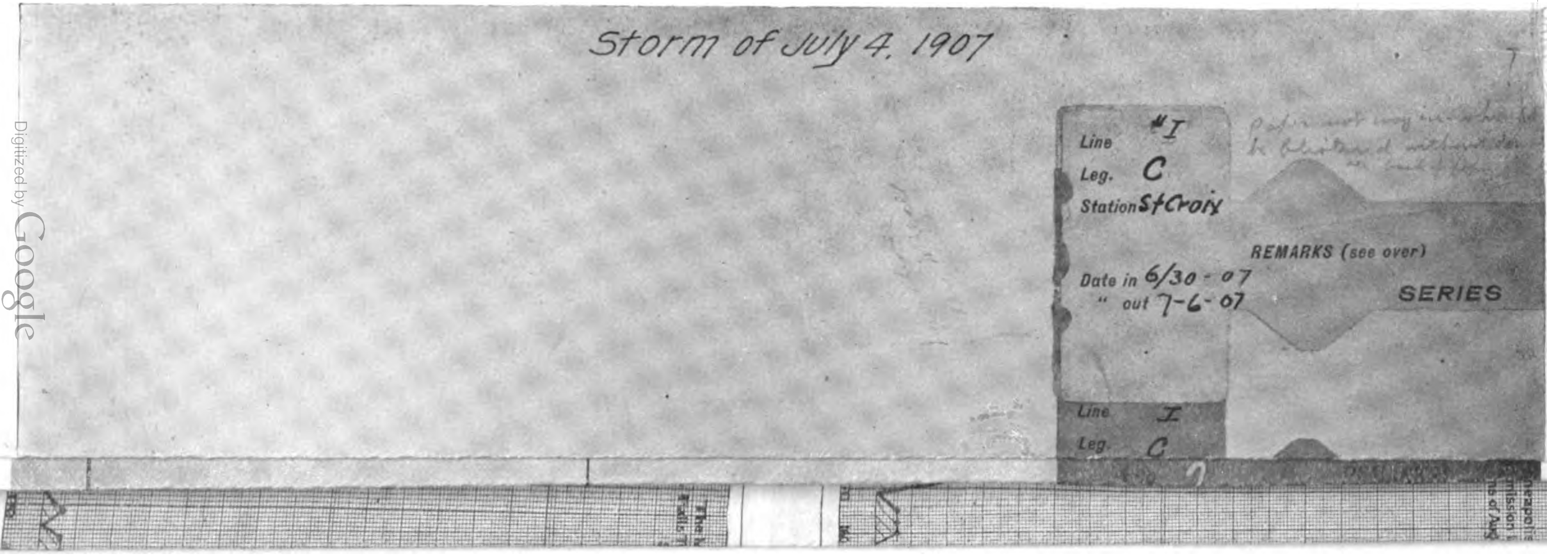
Date out 7-11

TAYLORS FALLS TRANS.

Date out 7-11

B

TAYLORS FALLS TRANS.



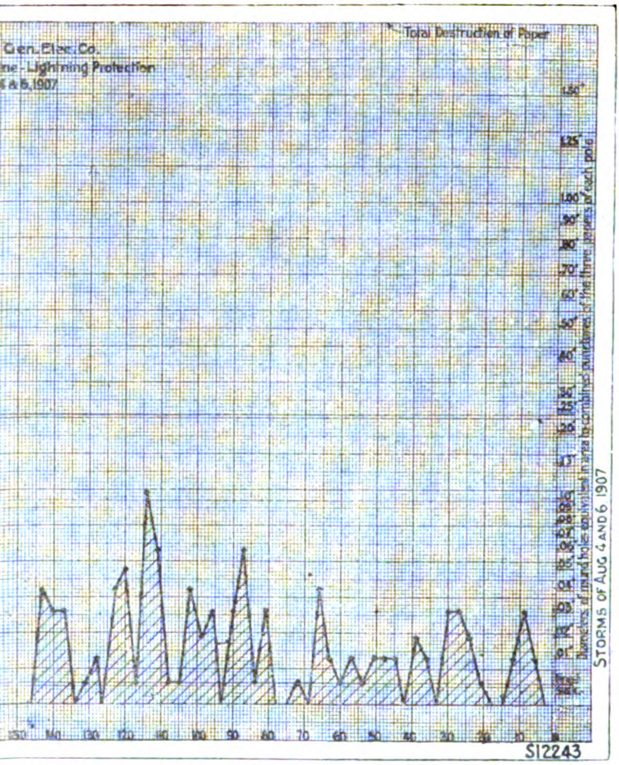
Storm of July 4, 1907

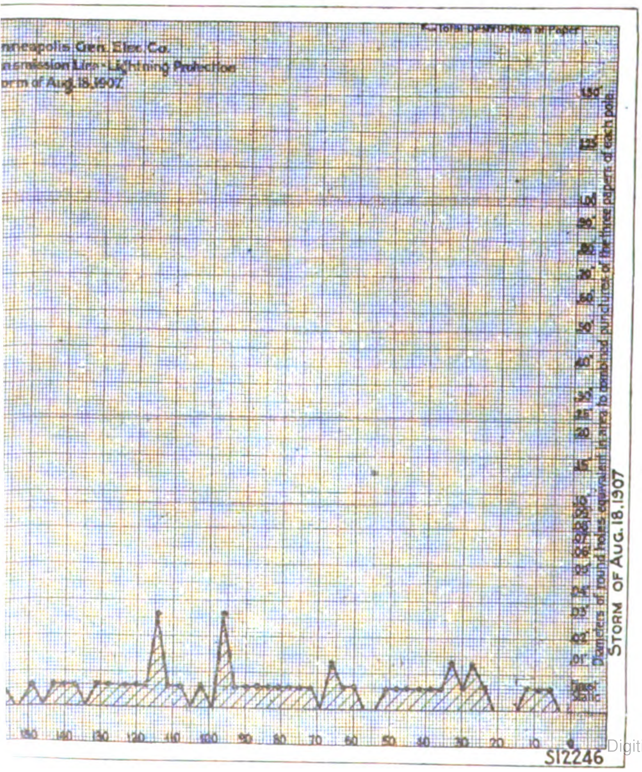
Line #I
Leg. C
Station St Croix
Date in 6/30-07
" out 7-6-07

REMARKS (see over)

SERIES

Line I
Leg. C


Gen. Elec. Co.
ne - Lightning Protection
5 & 6, 1907
Total Destruction of Paper
1.50"
1.25"
1.00"
.90"
.80"
.70"
.60"
.50"
.40"
.35"
.30"
.25"
.20"
.15"
.10"
.05"
.01"
Diameters of round hole equivalent in area to combined punctures of the three papers of each pole
STORMS OF AUG 4 AND 6 1907
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
S12243


nneapolis Gen. Elec. Co.
nsmission Line - Lightning Protection
orm of Aug. 18, 1907
Total Destruction of Paper
1.50"
1.25"
1.00"
.90"
.80"
.70"
.60"
.50"
.40"
.35"
.30"
.25"
.20"
.15"
.10"
.05"
.01"
Diameters of round holes equivalent in area to combined punctures of the three papers of each pole
STORM OF AUG. 18, 1907
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
S12246

line from induced static charges and in preventing insulator breakdowns.

In the only case of direct stroke, the lightning-rod pole alongside the line was effective in preventing line damage.

A grounded conductor running down the pole is of decided value in preventing splintering of the pole.

The selective resistance, multigap type of arrester is effective in disposing of ordinary disturbances.

The aluminum cell-type arrester is, in general, more sensitive and freer in discharge; it gives great promise for station protection.

Horn arresters of the series gap and selective resistance type are fairly sensitive to static discharge as well as to disturbances of lower periodicity, and of special value as emergency devices to relieve the station arresters in case of abnormal discharge. They may be adjusted to be fairly sensitive without interrupting service or necessarily throwing out synchronous apparatus.

The use of the tell-tale-paper system is essential in following the action of station protective apparatus, and is of decided value in studying line stresses and the effectiveness of protective devices.

The results of the above experiments have lead to the recommendation that the overhead grounded wire construction (Fig. 13) be immediately extended about 15 miles in sections covering both ends and the more exposed parts of the line; that the use of horn arresters be continued and further adjustments studied; that the rest of the station and line protective apparatus be left as it is; and that the present system of tell-tale paper and other records be continued during the coming season.

A paper to be presented at the annual meeting of the American Institute of Electrical Engineers, New York, May 19, 1908.

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(*Subject to final revision for the Transactions.*)

STUDIES IN LIGHTNING PERFORMANCE, SEASON 1907

BY N. J. NEALL

It is intended to discuss in this paper the general import to high-tension transmission of the data gained in 1907 as to lightning performance on the Taylor's Falls line, 50,000 volts, of the Minneapolis General Electric Co., and on the Presumpscot Electric Company feeders supplying power at 11,000 volts to the Cumberland Mills, near Portland, Me.

By reference to the description of the Taylor's Falls situation given by J. F. Vaughan, it will be obvious that in this case *line* disturbances chiefly are being combated; whereas, in the case of the Cumberland Mills, *station* disturbances have demanded attention.

These two classes of lightning disturbance will be considered separately in this paper.

Line Disturbances

Lightning disturbances to a long-distance transmission line may be due to an induced (bound charge on the line) direct stroke, or both.

Bound charge. This idea embodies the well known principles of the operation of a static charge imparted to any insulated body. When this charge is gathered from an electrophorous in demonstrating elementary principles of electricity, the amount of charge, its potential, rate of accumulation, and rate of leakage, are, certainly of small values compared with those, at least, that we consider in electrical engineering to-day, not to speak of what we imagine the magnitudes to be in lightning phenomena.

A modern high-voltage transmission line must be highly insulated from ground at every point; for 60,000-volt service, therefore, it is easily conceivable that, in general, a tremendous electric charge can accumulate on the lines—assuming of course perfect equipment—and be held there with relatively small leakage. When in such a case as bound charge release takes place from the line, due to the discharge to ground, or to another cloud from the exciting cloud, an enormous rush of discharge undoubtedly follows the first point of breakdown to earth. Now since this discharge may be well extended beyond the point of maximum strain, there is relatively a considerable *flow*, once the discharge begins. This flow can be conceived as taking place over a wide area, changing from a sudden or explosive character at the centre of the strain area to a gently quiet one at the more remote points.

Theoretically, there are no ready means of determining how great such an area might be; it depends on a variety of conditions, such as extent of clouds, the degree of their electrification, their direction and rate of travel, etc. Practically on the Taylor's Falls Line it has been shown that they may be as great as several miles in extent of line, or as short as 1000 feet, approximately. From the operator's standpoint, the worst these clouds can do, or at least the usual average, is the desired information.

It has been shown that all such charges, once they are free to move, tend to travel in waves, the progress and amplitude depending on the resistance in their path. In a limited length of line it may be easily possible to have the wave travel the whole length of the conductors, and be reflected at the open ends. This has shown itself prominently and repeatedly in the overhead grounded wires section tested by the Stone & Webster Eng. Corp. (See paper by J. F. Vaughan).

The tendency of such charges to travel in the transmission line is undoubtedly retarded very much by the skin-effect of the conductors; in fact, at the moment of release of bound charge we may consider that the charge has the choice of dissipating itself in three ways—along the line wires, over the insulators, or both. If the insulation is particularly good the charge endeavors to travel along the conductors. Its natural rate of doing so would be very high, in consequence of which there is a constant compromise between impeded progress along the wires and tendency to discharge over the adjacent insulator to ground. When the latter occurs, the rate of discharge is also likely to be again *suddenly* changed, and this, together with the absence of any inductance in the discharge path, is probably why tell-tale papers in such paths of discharge show violently explosive punctures.

Effect of discharge. From the data presented by Mr. J. F. Vaughan it has been shown that such discharges can be very violent and yet not harm the insulator, or produce a short-circuit. It has also been indicated that the discharges can be apparently of considerable length (compare static machine sparks) and yet make but a very fine hole in a tell-tale paper inserted in the discharge circuit. The presence of a thin long arc, or spark, which would of course be most pronounced in the case of " slow " discharge over a high voltage insulator, is then to be thought of as the detrimental factor in the failure of insulators from this cause.

Now, curiously enough, there is very little trouble reported from lines operating at lower potentials, even at potentials of 30,000 volts. If the theory advanced herein before as to the formation of static strains on a line holds true, then every electrical line must undoubtedly receive such strains. It is, then, an important question—why well extended low-voltage lines do not lose insulators more frequently? The answer is probably partly this: No line can take a charge much in excess of its maximum insulator arcing-over strength. The result is, therefore, that the higher voltage lines must handle a proportionately larger and higher potential static disturbance. The character of the insulators for this purpose, especially when one considers them as special forms of high-tension condensers, undoubtedly has a still further bearing on the damage resulting to the line. The tendency in high voltage insulator designs to form long " anticipatory " sparks and arcs is well known among insulator designers; this helps, therefore, to form a conducting path for the line voltage to produce grounds, short-circuits, or punctures, as the case may be.

Again the action of the insulator under simultaneous static discharges and line voltage may have an important bearing on such failure.

From the data gathered thus far from Taylors Falls Line I would conclude:

1. That a bound charge can be impressed on a transmission line, with an extent from approximately 1000 ft., perhaps less, to several miles.

2. That its presence at any particular spot cannot be predicted, and, save for well known locations established after years of

careful observations, must be expected at any part of the line.

3. That it may occur successively at a number of points on the line, provided the exciting storm-centre travels along the line, and that the line is long enough to meet the necessary lulls between disturbances, or recharging of the clouds.

4. That there is no measure as yet of its maximum magnitude, but there is reason to believe that this is very great.

5. That the better the insulation the greater the concentration, and consequent disturbance once the charge can start to ground.

6. That the size and shape of the insulator determine the character of the spark which passes to ground, and govern failure.

Direct stroke. The phenomena of spark-gap performance in measuring high voltages, or in discharging a static machine, may be profitably utilized in order to understand the action of direct strokes of lightning as they affect an electrical transmission line.

In order that a line may be struck at all it must lie directly in the region of greatest strain; that is, form one of the electrodes of the lightning spark-gap, the other being the distant cloud. As the strain gradually increases between the earth and the cloud, the poles of the transmission line simultaneously respond to the new conditions. Even though they are thought of as being partial insulators, this makes no difference in the preliminary stages of this phenomenon. At the same time the transmission wires are accumulating rapidly a heavy bound charge. As soon as the flash occurs, it may at first strike a pole directly, and only later take the path via the transmission wire over the insulator, once the escape to ground of the bound charge has thus paved the way.

Again, the flash may actually occur between the transmission wire and cloud, because in the gradual preliminary increase of potential strain the effect of the insulator, so far as the static equilibrium is concerned, is comparatively nullified. In either case the result is the same—shattered poles, if of wood, and perhaps shattered insulators.

Upon reflection, it is clear that the common expression, " to be struck by lightning ", is technically incorrect; for any terrestrial object that becomes an electrode for a lightning stroke, plays as strong a part as the complementary part of the exciting cloud. It is the behavior of the electrode when the spark passes that determines its resultant condition. To this may be ascribed the peeling off of the bark of a tree, shattered chimneys, etc., and may be conceived as effects of repulsion inherent in the articles themselves, either from electrical causes or excessive local overheating.

In the ordinary conception of direct strokes only one stroke is thought to pass between cloud and ground, but it is also known that direct strokes often consist of light branch strokes as well as the main stroke. Since, moreover, the line under strain presents a variety of points along which such discharges may play, it is easily conceivable that failure of the insulators may occur almost simultaneously in several adjacent parts of the line.

Photographic study of lightning flashes shows that it is apparently oscillatory, and there are in fact many strokes in an indefinitely short time, although the eye may see only one.

From the data at hand (Taylor's Falls) it appears that the *current* flowing at such times may be relatively small as compared with the lightning voltage. We then have on a grand scale a duplication of the static-machine sparks, and others of a similar nature.

The remaining primary disturbance is the discharge between cloud and cloud. If these are far enough away from the line the effect can be neglected, but owing to their generally low altitude such a discharge can either cause a release in the line of bound charges of opposite sign parallel thereto, or a secondary discharge between the clouds and line or ground as the case may be.

In either event the effect on the line is essentially the same as described in the preceding discussion, and may be either simple or complex; that is, at present, unless actually observed, it is impossible in some cases to tell exactly whether a transmission line disturbed by lightning has been affected by induced or direct stroke.

GENERAL

Effects of the nature of wireless waves. In addition to the conditions described in the foregoing paragraph, there are undoubtedly minor disturbances created in the line by the action of the lightning discharge as a source of high-frequency waves which, reaching the line, are absorbed in a manner similar to that of a receiver in wireless telegraphy. This absorption may be more rapid than the line can dissipate, and the result is either a surge of " static ", or, even worse, a discharge to ground, by reason of the impedance of the line wires to the free travel of the waves.

The result is, therefore, the same as in the preceding case—the imposition of a high peak of static on the line which tries to seek a level of zero value by traveling off in either direction on the line.

Effects arising from inherent characteristics of line construction depending on:

a. Insulator characteristics. An insulator for high-tension service is a form of condenser made up of a number of condensers (petticoats) of larger capacity, placed in series between line and ground. The best interest of the designer is, therefore, so to apportion his parts as to insure a uniform distribution of strain best suited to the service required. When this is but poorly attained there occurs the well known failure of insulators on test by premature puncture of one of the parts.

In addition to the absolutely essential qualities of ruggedness, high-class dielectric strength, and good finish, an insulator for such service must have a strength against arcing over at normal frequency at certain values previously determined upon by the designer. In general, insulators are designed not to arc over at below twice the voltage of the system on which they are to be used when subjected simultaneously to some such rain test as 0.25 in. per min. driven against the insulator at an angle of 45°. This, so far as it imitates nature, is of course very severe, and gives for any design a much lower voltage of arcing over than would be obtained with the insulator dry.

In testing such insulators the usual practice is to raise the voltage fairly quickly until arcing over occurs; if this falls below the desired voltage the design must be changed. An insulator can, in general, stand a higher voltage thus administered than voltage applied continuously.

Some insulators are designed for large total lengths of surface to prevent leakage; and where this is not likely to be linked with severe lightning disturbances the design of the insulators can be made in a different way. It might be said, however, that the insulator thus designed is likely to make a poor showing under rain test, while it is not at all improbable that for all-round service the insulator well designed for lightning and rain may do well in the leakage class. It is not the purpose of this paper to consider the latter.

On the rain test at present, therefore, we look for characteristic performance. Two phenomena exhibit themselves: first, the static strain, or envelope of the insulator repulses the drops of falling rain away from itself; secondly, the combined forces of static repulsion and mechanical deflection of the falling rain give rise to a resultant direction of rain, which, if the inner petticoats are not properly shaped, throws the water directly under the top petticoat. In general this has been found to be most pronounced in curved petticoats and absent in straight parts when properly inclined. It is obvious that the former condition is very harmful to the strength of the insulator under high-potential strains. In addition to this, many insulators give evidence of internal unbalance long before breakdown. This usually means an insulator very liable to puncture.

So far as the insulator used on Taylor's Falls line is concerned, I wish to state that standard tests which I have made independently on this type show a satisfactory performance along the lines indicated in the preceding; this leads me to think that its characteristics are of distinct value in the lightning problem now under consideration.

Now the preceding characteristics apply entirely to insulator performance at *normal* or commercial frequencies. At higher frequencies there is as yet very little data, but the following ideas may be tentatively considered as an aid to the present discussion.

Equivalent spark gap. In testing insulators to date no consideration has been given to their equivalent spark gap. For very high voltage insulators this is hard to secure for the general want of adequate apparatus but, it is undoubtedly within the reach of some. The principle involved is this: that while an insulator may have a very good performance under normal frequencies, it may be very poor at high frequencies, or their equivalent.

Nature of discharge. It is not inconceivable that the discharge over an insulator may be tenuous as well as abrupt. If tenuous, the shape of the petticoats once again materially affects the disposition of the arc, and possibly causes a fracturing by means of the intense local heating and the consequent unequal expansion of the porcelain. There may also be " percussion " effects due to the sudden change of atmospheric pressure around the insulator at the time of arcing over, and thus fracture an insulator. These ideas are based on the characteristics of shattered insulators on the Taylors Falls Line.

Simultaneous static discharge with line voltage. This is the equivalent of static discharge over a lightning-arrester with voltage simultaneously present. In the case of insulator performance, the object of the instigation should be to determine the degree of non-arcing power of any given design under the conditions noted.

b. *Mechanical design.* The nature of the line construction, whether of wood, or entirely of metal, the length of span, size of insulator, number and nature of braces, etc., determines to a large extent the degree of damage any lightning disturbance will cause. If the poles are of wood, splintering of the poles may often occur, sufficiently, at that to require renewal of the support. Short spans naturally subject more poles to disturbance, within a given area, and, therefore, to more likelihood of damage. Large spans on metal towers invite more trouble (relatively at a given support) because of their isolation and attraction for the charge.

c. *Line profile and local topography.* Attention has long since been called to the relation between the topographical location of the line, and it vulnerability to lightning. In any layout of importance the profile, or cross-section of contour, should be made in order to show the maximum and minimum elevations and relations of hills to valleys in the line. Where geological formations are known, the extra information thus given is of value in determining the probable points of discharge between cloud and ground, provided the general direction of a storm is also fairly well established. This feature has been demonstrated on the Taylor's Falls line by the apparently greater vulnerability of the west side of the line over the east, direction of storm from northwest to southeast. It is also thought that lightning has shown a preference for striking high elevations of the line and in damp, swampy places.

d. *Proximity of sub-stations.* It is just as possible for a lightning discharge to occur near a power station as not, in which event ordinary lightning protection would be heavily affected. It is doubtful whether any device now proposed for station protection, exclusive of horn lightning arrester without appreciable effective resistance in series, could handle successfully a release of heavy bound charge, etc. It is, therefore, important to insure adequate protection at such points. On the other hand, the tendency of line disturbances to concentrate might render any station immune if sufficiently remote therefrom. These conditions have been amply illustrated on the Taylor's Falls line.

METHODS OF PROTECTION

From the data given by this line, and on the basis of the preceding considerations, both theoretical and practical, the following methods of obtaining protection against line disturbances from lightning may be considered:

1. *Overhead grounded wire.* Judging alone from the data now at hand as to its behavior, an overhead grounded wire placed near the line conductors may be considered beneficial. Apparently, it is not necessary for the grounded wire to be above the transmission wires in order to absorb a certain portion of the static charge. This has been positively measured in the case of the grounded wire in the centre of the triangle on the Taylor's Falls Line, and is doubtless helpful in reducing the strain. Its limitations in this respect are obvious, especially when it comes to increasing the amount of ground wire protection over that given by one wire.

The ideal static protection, as is known, would be a metallic envelope for the line; but since this is not commercially feasible, it is thought possible to approximate it by supporting several grounded wires above the line. These wires are so placed with reference to the line wires that an imaginary plane, extending at an angle of 45° from the wire on either side of centre, will just pass over the transmission wire. There are as yet no positive data to show the value of this consideration, but there are data of a definite nature showing the effectiveness of the double-wire overhead grounded-wire protection.

When the possibility of simultaneous direct stroke is borne in mind, a further disadvantage of the grounded wire placed *within* the triangle is at once apparent; for a direct discharge between this wire and cloud is not easily conceivable, certainly not so conceivable as in the external arrangements of grounded wires where the possibility of divergence of direct stroke is better prepared for.

The experimental data on this performance have not yet fully and completely established the superiority of type, but there is certainly good reason to think that an overhead grounded wire protection, consisting of several wires supported above the line, is good protection. This protection should reduce the disturbance to the line to a very small amount indeed. In fact, the power of absorption shown by such protection leads to the conviction that if a transmission line were so equipped throughout, very little static disturbance would ever reach the stations;

in other words, the overhead grounded wire would not only shield against the line troubles, but reduce consequent station disturbances.

2. *Lightning-rods.* There is evidence to show the value of lightning-rods to a transmission line, particularly in that case of Taylor's Falls where a lightning-rod was struck and the tell-tale gaps on the line adjacent thereto showed no disturbance. This diverting power is certainly of value. Two methods of application are feasible, first, as an additional feature of line protection placed separately but adjacent to the line at points known to be particularly subject to this effect. Since the latter is at best uncertain, I prefer the inclusion of a lightning-rod with the overhead grounded protection at frequent intervals throughout the line. On a steel tower construction (solely because of the usually long spans) these should be placed on each tower; on a wood-pole line, one of these could be placed at each grounded pole. These rods should perhaps extend 4 ft. to 6 ft. above the overhead grounded wire, and end in spreading tips.

3. *Grounds.* The importance of good grounds for the overhead grounded wire is patent. Too great care cannot be exercised in this direction. The data given show that even on the grounded wire the passage of the charge to earth is apparently impeded, even by the short distance it had to travel along the line. For this reason it is clear that grounding at every hole is beneficial to the discharge. For ordinary line work time may prove that grounding every several poles is adequate, but that near stations or important points of the line, grounding at every pole is essential. This would be particularly desirable in the case of partial protection of the line where a stretch of overhead grounded wire was used to protect a sub-station. In this case the data as to the possible extent of such charges make two miles, approximately, the minimum limit of length out from the station that would secure nullification of any nearby induced disturbances.

4. *Extent of application.* It is an open question of economy whether to equip a line completely, or partially, with overhead devices; but in consideration of the charges which they may be called upon to carry *at any point*, the whole line protected is theoretically and generally the safer policy.

5. *Insulators.* The Taylor's Falls data show that while the overhead grounded wire appears to remove the greater part of

the stress, yet it should not be assumed that the remaining charge is negligible.

For this reason the selection of insulators for such a service should insist on as high quality as ever before. The criterion of approval should be a non-arcing at no less than double normal potential under rain test of 0.25 in. per min. at 45°, with pin grounded, or an equally severe test. Under such a test the insulator should be relatively free of premature arcs and sparks. No rain should be deflected under superposed petticoats, and thus promote breakdown. When possible the equivalent spark gap of the insulator should be determined, and should always be high, certainly giving a large margin over any standard lightning protective apparatus connected to the line.

The reason of this is patent from the performance of insulators on high-tension lines. It is clear that when the line is running with the neutral grounded the severity of service on the insulator because of the resulting short-circuit arc is certain to be quite destructive. In this respect the ungrounded system is better because the discharge over the insulator does not necessarily mean a short-circuit, or, if two insulators on opposite phases should simultaneously discharge, the resulting short-circuit may be favorably effected by the intervening resistance conditions involved.

The performance on the Taylor's Falls line brings out an important element of high-tension transmission line design; namely, the probable extra vulnerability of the insulators on all-steel towers, cross-arms, and pins. Where a section of wooden cross-arm intervenes between the insulator and the nearest ground it is possible to conceive of an increased arcing distance, which in the case of small insulators might be of some benefit in holding back disturbances. I therefore conclude:--If the insulator can be properly selected as to size, equivalent spark gaps arcing over voltage, and general characteristics, the nature of the tower construction may be neglected, particularly if overhead ground protection is present.

6. *Line choke-coils.* At the suggestion of Dr. Steinmetz, line choke-coils were originally included in the program of experimental equipment for Taylor's Falls Line, in order to determine by means of tell-tale gaps how far any given disturbance travelled along the line. The experiments from which these data were to be obtained were not carried out, but the choke-coil papers show that the coils operate freely under the static disturbances

which are now known to be present on the line. In consideration of the small inductance of these coils (1 ft. diameter by 20 turns, approximately 60 ft. of wire) the tell-tale indications of static rushes are most impressive.

The chief difficulty in such an equipment is in the construction of the choke-coil itself. For the Taylor's Falls line the coils were finally constructed of brass tubing, which has apparently been found reasonably satisfactory. It is yet too early to say whether such a feature can be of great benefit. The danger of such an equipment is the possible piling up of potential at the nearest insulator, and the consequent failure of the same.

7. *Horn lightning-arrester.* The horn lightning-arrester (essentially a simple spark gap of special form between line and ground) is, so to say, a hybrid—part station, part line device. In this paper it is considered solely as protection—extraordinary against great disturbances of any source reaching a sub-station or power house.

a. *Gaps.* I think it must be clear from even this one season's records on the Taylor's Falls Line that when a horn arrester is at the centre of a violent static disturbance, for example, a disturbance that affects the insulators, it will act as do the insulators—arcing freely over a large distance. In this way, by proper relative adjustment of the various gaps, severe disturbances near important points can be carried off without damage to either the insulator or the station apparatus. Judging from the magnitude of the static discharge as evidenced on some of the line tell-tale papers, it is a grave question whether standard station lightning-arresters could take care of anything like a nearby direct stroke. There is less doubt that the horn arrester could do so. In the case of grounding of the line, the horn gap will also operate, but in my judgment such action should be made as difficult as possible, in consideration of the sensitiveness of the electrolytic arrester to this effect. This leaves the horn arresters to care for emergency disturbances like a direct lightning stroke and high-power surges only.

On the Taylor's Falls plant there has been a pronounced evidence of the effectiveness of a number of gaps between line and ground operating on the selective path principle. In general the operation of the gaps has recorded both lightning disturbances and disturbed static balance from grounding of the system. In the former case all of the gaps between line and ground would operate, the tell-tale paper sometimes indicating a light discharge not followed by dynamo current, and again quite a heavy line current. The methods adopted apparently establish this action very well, irrespective of the arrangement of the resistances, whether directly in shunt as in the power house group, or directly in series, as at Hugo. The curious preference for the circuit through the fuse to ground at the power-house horn instead of from the shunt lead to ground—the resistance being relatively equal in all directions—shows forcibly the ease with which such disturbances take a long *air* path in preference to the regular circuits prepared for them.

b. *Resistance.* In the matter of resistances there are as yet incomplete data on the behavior of water, but certainly the operation of the last season did not exhibit any bad traits in this material. At the power house the water for the whole arrangement is supplied by the tailrace, and is, therefore, constantly renewed. Its resistance, however, is low. My fear was that a discharge to ground would go by way of the first path to shunt resistance, and thus directly to earth. I find, however, that it has apparently not done so, and I conclude that this is due partly to the superior character of the horn arrester " ground " reached through the fuse (see paper by J. F. Vaughan). The tanks at Hugo and at the sub-station have given no trouble. The amount of resistance best suited to the purpose is yet to be worked out. It may be that the size of receptacle employed, as well as the method of arranging electrodes,* has perhaps had an important bearing on this matter. The use of bituminized fibre conduit enables high insulation at the point of entrance of the leads, and controls the degree of electrode exposed in the water for the passage of the discharge.

c. *Operation.* In general, it must be borne in mind that if the horn is to carry any current, the *more* current it carries the better, so far as self-extinguishing power is concerned. This, however, is bad for the system, tending to pull out the breakers. The employment of light fuses so limits the discharge that protection is lacking where disturbances repeat themselves. The selective path multigap type of horn (gaps arranged in series as at Taylor's Falls and Hugo see paper by J. F. Vaughan) permits a better adjustment theoretically, to the variables of such disturbances, and insures less need of attention.

It is recognized that water resistances must be put out of commission in winter, unless special provision be made for keeping them warm. Where such apparatus is near a substation, this is not difficult. In such a situation as the middle of a long-distance transmission line it is still feasible but scarcely necessary. Since its chief use may here be considered in connection with lightning disturbances, there remains only the possibility of high-power surges which could be easily provided for by a proper adjustment of the horn gaps in series with a fuse. Even in this case a fuse might be retained of considerable current capacity, and depend solely on the gap action to relieve the strain.

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*This method was suggested to the author by Mr. John L. Harper.

It seems desirable to have the horns operate coördinately with the arcing over characteristics of the insulator. Since the grounding of the line may cause a momentary potential rise at some distant point, owing to the rush of line charging current to its new position of equilibrium, the setting of the first gap in a selective-path type should be approximately 150% normal voltage with reasonably high resistances. Too high resistance would impede the discharge. The total gaps in series should breakdown just under the arcing-over voltage of the insulators under its worst performance, usually taken to-day as at rain 0.25 in. per min., angle 45° with pin grounded. It were better with a single gap to have no resistance in series, only a fuse, to be set for the highest voltage.

These considerations are subject to change with increase in knowledge as to actual equivalent spark gaps of insulators, lightning-arresters, and horn air-gaps. It may be possible later to call for larger air-gaps, in the horns, because of its equivalent spark gap characteristics. The present ideas are recorded merely to illustrate the purposes and tendencies for the future in the Taylor's Falls installation.

A horn arrester should preferably not be called upon to operate on any condition which a standard station lightning-arrester could handle.

The bad effect of wind on the arc has been well indicated by both experiment and actual operation. This feature of horn lightning-arrester operation will always be a serious menace to a system at the time of simultaneous operation of two adajcent horns; it is a matter of chance which must be allowed, or elaborate preventive precautions must be taken.

8. *Special line-protection station.* The operation of the horn arrester group at Hugo (centre of the line) Taylor's Falls is critical in that it focuses the whole question of placing station type arresters on the line to draw off the static disturbances.

It is clear from the data now at hand as to the minimum area of local concentration of lightning line disturbances approximately 1000 ft. that in order to do this fully a very large number of arresters (approximately six groups per mile) would have to be installed, and then, aside from the consideration of maintenance, there is the great question as to their reliability and sufficiency under the conditions. During the past season I have had a group of low-equivalent alternating-current lightning arresters, equipped besides with phase to phase protection, at the middle of a 11-mile, 11,000-volt line, in Maine, to assist in carrying off discharges from the line; for there has been considerable action at this plant from lightning. The characteristic of the performance of this system as a whole is a phase-to-phase operation, rather than from line to ground. Even though lightning storms were particularly frequent in this locality, and station protective apparatus at both the generating and step-down ends of the line operated freely, with considerable dynamic current manifested, the discharge at the centre of the line was nearly always lighter and colorless. To such a degree does this check the performance of the central arrester group on Taylor's Falls line, that I am inclined to conclude that for the majority of line disturbances, whether static or otherwise, a central group does little good. What a high-power surge would do is still an open question.

While these conclusions do not destroy, theoretically, former practice in regard to frequent placing of station arresters on the line, they seriously modify its practical value. By the theory advanced that the better the insulation of the line the more local the serious static disturbances will be, then line arrester stations decrease in value as the design voltage of the line increases. They thus become self-eliminating from our consideration.

9. *Miscellaneous.* So far as attempts have been made to protect against line disturbances by larger insulators, or special features at insulators, such as horns to modify the effect, it is clear there is no reduced interruption to service itself when discharges actually occur. For this reason I should prefer, where feasible, any protection scheme which aims to prevent the static disturbances getting on the line at all.

STATION LIGHTNING PHENOMENA

The characteristics of this feature of lightning disturbance to electrical apparatus are too well known, and too fully discussed, to need further mention here. For the sake, however, of new corroborative data, which I now wish to offer, I will summarize the phenomena as follows:

1. Lightning effects causing line-to-ground disturbances.
2. Line-to-line disturbances.
3. High frequency (or equivalent) and low frequency.
4. Internal disturbances due to grounding of line, short-circuits, etc.

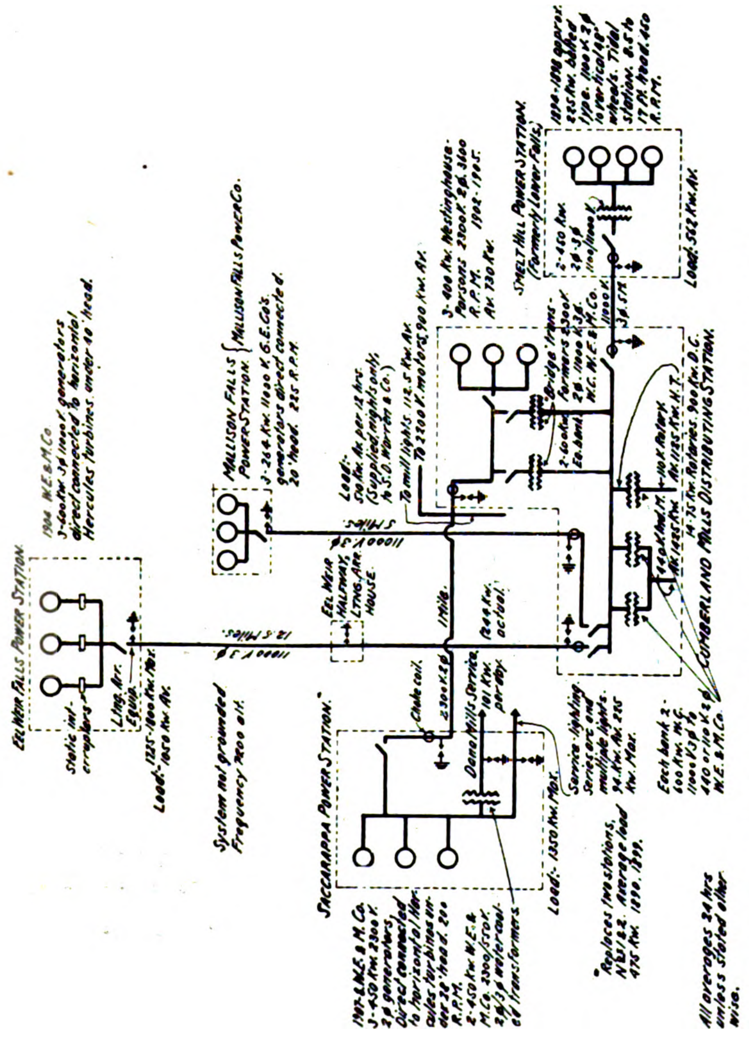
Line-to-ground. From the station data at Taylor's Falls power house, as well as from the Minneapolis sub-station, the frequent and full operation of all types of station protection is fully established. As has been stated by Vaughan, throughout the season of 1907 no apparatus was hurt by lightning, save in the case of one transformer bushing, which failed by grounding.

The lively operation of the apparatus, as evidenced by the action of the series and shunted gaps, respectively, and the heavy discharges over the electrolytics, indicate a considerable strain to ground, which for the present must be considered effectively handled by the protective apparatus.

The size of the punctures over the low-equivalent alternating-current arrester does not differ materially from similar data on apparatus for lower voltages. In consideration, however, of the data now at hand as to the action of static discharges on the line and the effect on tell-tale papers where free discharge occurs, there is a question whether or not station lightning protective apparatus must not be limited in action to reflected or transmitted disturbances of lesser magnitude, and to such disturbances as are generated in the system itself. Certainly, commercially we cannot expect more than this. Comparing the action of the various types, it has been shown that no arrester shunts the other entirely. Thus while from the response to ground the greater sensitiveness of the electrolytic is apparent, yet in case of greater severity all arresters operate.

I recognize that, theoretically, both types should operate at the same point, but in the case of the electrolytic arrester the possibility of a closer adjustment to circuit conditions without consequent short-circuit is greater than in the low equivalents or other multigap resistance types of arresters.

At the plant of the Presumpscot Electric Company, previously referred to, a large amount of experimenting has been carried on for the last two seasons, and is still under way. This plant consists of three hydroelectric stations feeding a central distribution station, (Fig. 1) where the power at lowered voltage is conveyed to a large synchronous converter load and induction-motor load respectively, one of the stations generating directly at 11,000 volts.


EEL WEIR FALLS POWER STATION.
1904 W.E.&M.Co. 3-600Kw. 3ϕ 11000V. generators direct connected to horizontal Hercules turbines under 40' head.
Static interrupters
Ltng. Arr. Equip.
Load:- 1225-1800 Kw. Max. 1050 Kw. Av.
System not grounded Frequency 7200 alt.
11000 V. 3ϕ
12.5 Miles.
MALLISON FALLS POWER STATION. {MALLISON FALLS POWER CO.
3-264 Kw. 11000 V. G.E.Co's. generators direct connected. 20' head. 225 R.P.M.
SACCARAPPA POWER STATION.*
1907-E.W.E.&M.Co. 3-450 Kw. 2300 V. 2ϕ generators, Direct connected to horizontal Hercules turbines under 38' head. 200 R.P.M.
2-450 Kw. W.E.&M.Co. 2300/550V. 2ϕ/3ϕ water cooled transformers.
Choke coil.
2300 V. 2ϕ
1 Mile.
Dana Mills Service. 101 Kw. per day.
1244 Kw. actual.
Load:- 1350 Kw. Max.
EEL WEIR HALFWAY, LTNG. ARR. HOUSE.
11000 V. 3ϕ
5 Miles.
Load:- 510 Kw. Av. per 12 hrs. (Supplied nights only, to S.D. Warren & Co.)
To mill lights. 112.5 Kw. Av.
To 2200 V. motors, 900 Kw. Av.
3-400 Kw. Westinghouse-Parsons 2300V. 2ϕ. 3600 R.P.M. 1902-1905. Av. 730 Kw.
"Bridge" transformers 2300V. 2ϕ. 11000 V. 3ϕ. W.C. W.E.&M.Co.
2-600 Kw. Ea. bank.
11000 V. 3ϕ. 5 M.
SMELT HILL POWER STATION. (Formerly Lower Falls.)
2-450 Kw. 2ϕ-3ϕ 1100/11000 V.
1894-1898 approx. 225 Kw. belted type. 1100 V. 2ϕ 10 vertical 48" wheels. Tidal station. 8.5 to 17 ft. head. 450 R.P.M.
Load: 562 Kw. Av.
Service lighting. Series arc and multiple lights. 94 Kw. Av. 285 Kw. Max.
*Replaces two stations, No. 1 & 2. Average load 475 Kw. 1890, 1899.
440 V. Ind. M. Av. 1425 Kw.
110 V. Rotary. Av. 1185 Kw. H.T.
14-75 Kw. Rotaries. 900 Kw. D.C.
Each bank 2-600 Kw. W.C. 11000 V. 3ϕ to 440 or 110 V. 2ϕ W.E.&M.Co.
CUMBERLAND MILLS DISTRIBUTING STATION.
All averages 24 hrs unless stated otherwise.

DIAGRAMATIC SKETCH OF TRANSMISSION LINES. PRESUMPSCOT ELECTRIC CO.

FIG. 1

In consideration of what appeared to be pronounced line to line characteristics each protective apparatus equipment on this system was supplied with extra gaps and fuses (until best adjustment should have been accomplished) and in one case low equivalent arresters were placed across the line. In addition to this the regular low-equivalent arresters between line and ground were shunted with gaps and fuses, two each, around the shunt and series resistances in series, (Fig. 2). The whole system was carefully equipped with tell-tale papers so that nothing could happen without leaving a record.

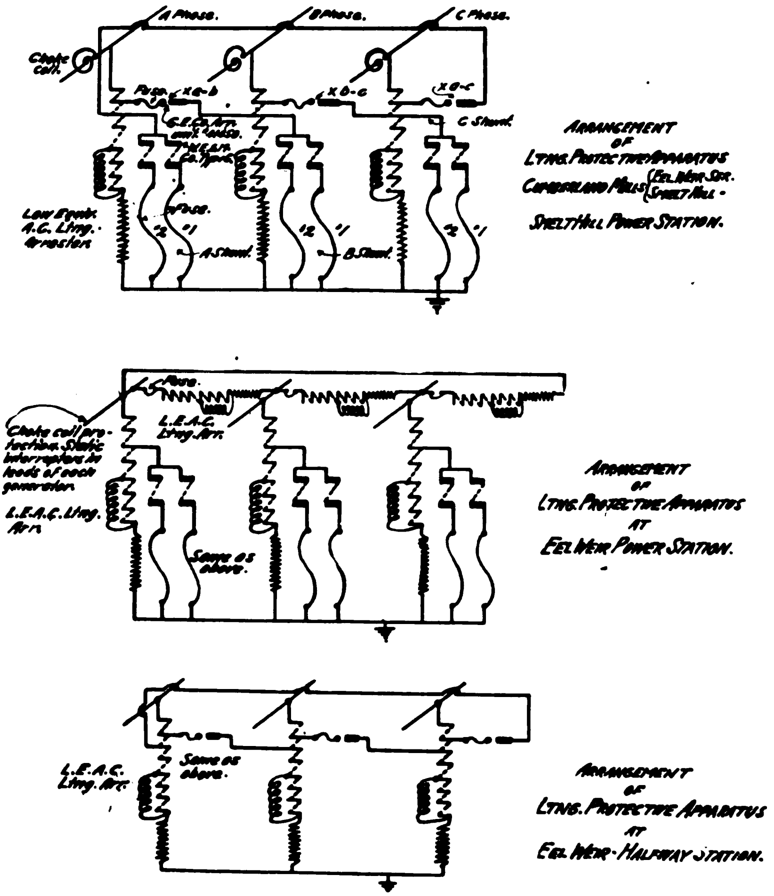

A Phase.
B Phase.
C Phase.
Choke coil.
Fuse.
X a-b
X b-c
X a-c
G.E.Co. Arr. with X ranged.
W.E.&M. Co. Type
C Shunt
Low Equiv. A.C. Ltng. Arrester
Fuse.
#2
#1
A Shunt.
B Shunt.
Arrangement of Ltng. Protective Apparatus Cumberland Mills {Eel Weir Sta. Sheet Hill - Shelt Hill Power Station.
Fuse.
Choke coil protection. Static interrupters in leads of each generator.
L.E.A.C. Ltng. Arr.
L.E.A.C. Ltng. Arr.
Same as above.
Arrangement of Ltng. Protective Apparatus at Eel Weir Power Station.
L.E.A.C. Ltng. Arr.
Same as above.
Arrangement of Ltng. Protective Apparatus at Eel Weir - Halfway Station.

FIG. 2

The results to date are as follows:

Improved service during lightning storms.

When the arresters operated to ground there would often be a complete action over the low-equivalent arrester between line and ground as well as over the gaps and fuses in shunt thereto.

In any given discharge not all the fuse paths to ground would operate. Fuse paths in operation would sometimes blister the paper badly, again a paper would show burning.

Fuses did not always blow even though a discharge had passed

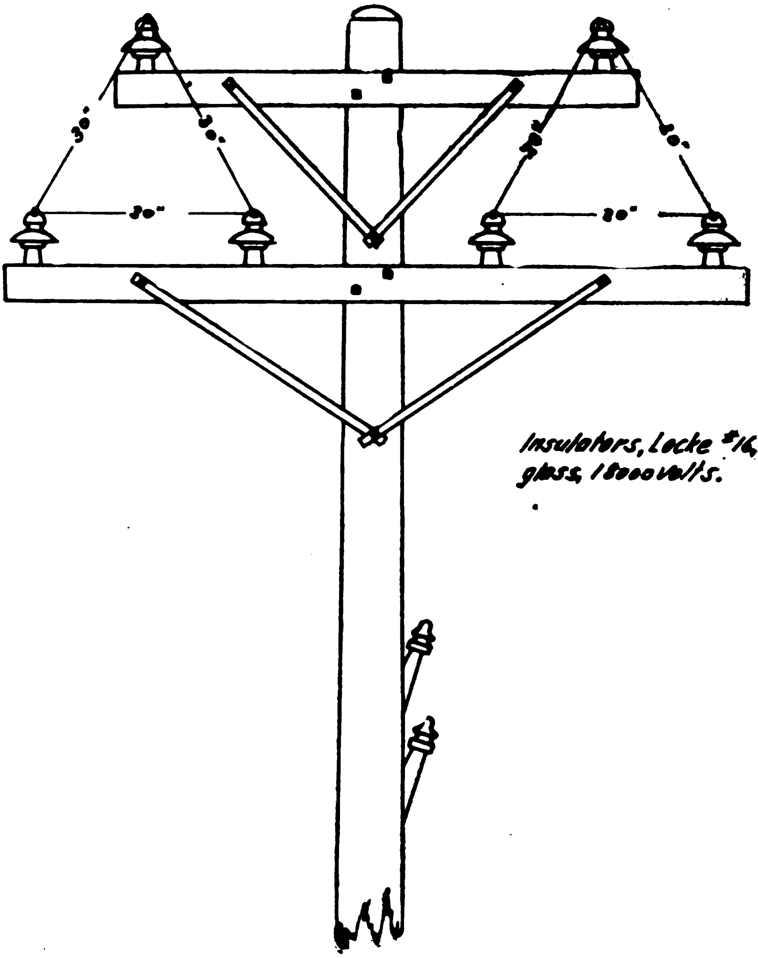


FIG. 3—Detail of Eel Weir line construction Presumpscot Electric Co.

over them. The action over the fuse paths was apparently freer than over the arrester; that is, tell-tale papers on the fuse path showed larger holes and greater blistering.

The shunted-gap papers seldom show any current, from which, together with data from other sources, I conclude that

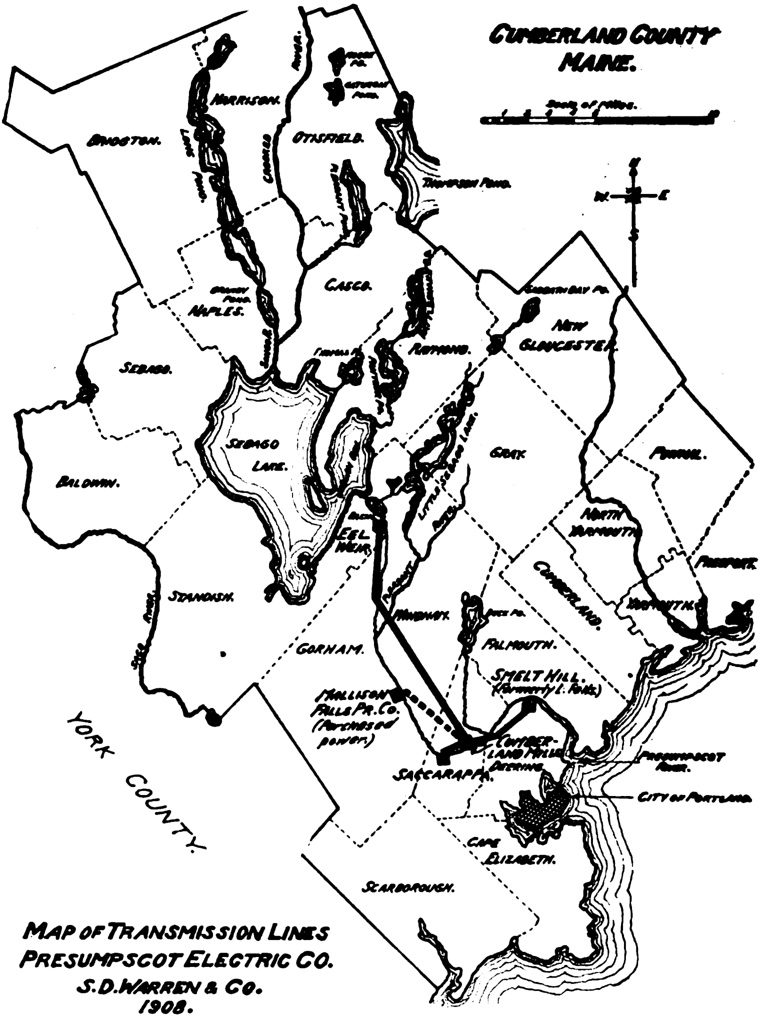


FIG. 4

Presumpscot River is one of the most interesting as well as one of the best water-power streams of its size in the United States. It is the outlet of Sebago Lake, which lies about 17 miles northwest of Portland. The lake is fed by Crooked River, a stream heading 35 miles farther north and within 3 miles of the Androscoggin. The area of the lake is 46 square miles; the total water surface on the drainage basin is 97 square miles; the area of the drainage basin at the outlet of the lake is 420 square miles, and at the mouth of the river 600 square miles. According to the survey made by Joseph A. Warren, of Cumberland Mills, the fall from the crest of the stone dam at the foot of Sebago Lake to mean low tide at the foot of the lower falls is 265.16 feet in a distance of 21.65 miles, or an average of 12.25 feet per mile.—*From U. S. G. S. Water Supply Paper. No. 201, p. 72.*

the dynamic *current* seldom passes over the shunted gaps. It is the static or disturbing voltage only.

A new type of selective resistance arrester was installed last season, but too late to give much information. It has operated on several occasions, but there are as yet insufficient data to permit full comment on its performance.

Line-to-line. The results in this item at the Presumpscot Electric Company have been most interesting. They are:

A firmly established record of the existence of line-to-line disturbances in addition to those disturbances usually considered in lightning arrester operation. These disturbances were found to be taking place during "uneventful" periods of operation, with nothing to show from the general indications why they had happened.

Evidence, also positive, that line-to-line phenomena apparently act like static line disturbance, both "slowly" and "suddenly". This was evidenced by getting punctures in the shunt-gap papers of the low-equivalent alternating current arrester line-to-line equipment at Eel Weir Power Station. In another case the resistances of the low-equivalent arresters used for phase to phase protection were fused. To do this, means a potential that could hold long enough over the series gaps and shunts and series resistance in series to fuse the wire. This, was however, a rare occurrence.

Indications existed that line accidents, such as the wind blowing the wires together, will cause a wave of phase-to-phase disturbance to travel a long distance and operate the phase-to-phase protection; that on the closely adjusted gap sets the fuses invariably blew; and that some phase-to-phase action nearly always accompanied phase to ground operation.

A summary appended hereto shows the relative number of times, etc., this apparatus operated. From this I feel safe in drawing two conclusions: first, that proper line-to-line protection is as essential as line-to-ground protection. Thus confirming Wirt's contention. Secondly, that the line-to-line operation is likely to take relatively considerable time, and, therefore, that in the long run high and stable resistance in the discharge path is necessary for uninterrupted operation. A shunted-gap equipment, however, may be valuable.

Since phase-to-phase protection can be easily added to any multigap arresters not already so provided for, its adoption is not difficult.

I have assumed that it is as necessary for high-voltage installations as for low-voltage, for although I have as yet no data on this feature I believe it will be found there also. For this reason I would favor electrolytic arresters arranged in star with a common jar or jars to ground, since this does not impair the line-to-ground protection, and adds to the phase-to-phase.

RECORDS OF OPERATION

I wish to call attention specifically to the fact that all the evidence on which these remarks are based is not speculative but *actual*; that is, assured by tell-tale papers placed in the discharge paths at all parts of the respective systems.

It is safe to assert that in the case of Taylor's Falls, it has furnished us with data of great value to electrical engineering. In the case of the Presumpscot Electric Company it has enabled us to study very closely the operation of the system, to eliminate uncertainties, and to adjust conditions accordingly.

In both cases it has called for the employment of a large number of tell-tale papers, and an irksome filing of the same, but in my judgment the results have more than repaid us for the labor. In this connection, I recall that probably the first investigation of this character was made by A. J. Wurts to determine the necessary line protection in street railway service.

The U. S. Weather Bureau has it in its power through its local stations to help immensely in determining the local characteristics of lightning. These are of great importance to the problem as a whole.

SUMMARY

As a result of the studies in lightning phenomena on Taylor's Falls and Presumpscot Electric Company's circuits, herein discussed, I would add the following summary on this subject.

Line disturbance by lightning.

1. Lightning disturbances on a line are more than likely to be local varying approximately from 1000 ft. or less, to several miles. The longer areas being less frequent.

2. They are likely to happen at any part of the line.

3. A direct stroke of lightning is not necessarily harmful: it depends upon the quality of the stroke, etc.

4. A line may be affected by a bound charge and direct stroke simultaneously. There is as yet no evidence to enable these to be measured separately.

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* A.I.E.E. PROCEEDINGS, Vol. XXIII, p. 558.

5. Any grounded wire suspended on the line will tend to absorb a charge.

6. An overhead grounded system of one wire, two wires, or more, *above* the line wires is desirable.

7. An overhead grounded wire should be grounded at every pole near stations and important places, otherwise at every several poles.

8. When an overhead grounded wire is used exclusively for station protection, it should not be less than two miles in length and be grounded at every pole.

9. The higher the voltage design of the line the greater the possible disturbance from lightning to the line. High-voltage lines, therefore, need, more than low voltage ones, overhead grounded wire or its equivalent.

10. Lightning-rods added to the overhead grounded system probably add to the protective power. The full value of this is not yet determined.

11. Shattered insulators are liable to occur in every severe thunderstorm, but not in light ones. Puncture is more probable with power on the line at the time.

12. Insulators should be carefully selected for the service, to test not less than two times normal voltage between line and pin with pin grounded. The equivalent spark-gap should be higher than any arrester path to ground on the line.

13. Horn lightning-arresters should be employed for extraordinary service only. The general arrangement known as the multigap selective path type promises to be of value.

14. Lightning-arrester stations to discharge line disturbances become increasingly expensive, and of questionable assistance the higher the voltage transmitted. Their total number depends on the length of line.

15. Wood poles may be effectively protected against splintering from lightning discharge by providing them with a small metallic conductor to ground.

Station protection.

17. Electrolytic lightning-arresters have so far behaved creditably, particularly in sensitive relief of grounds, but do not indicate a complete superiority over other types.

18. Line-to-line protection is desirable.

19. Apparently there cannot be too much protection on a plant. Every lightning-arrester added plays a part, but *practically* there is a limit. For many reasons it is obviously de-

sirable to keep the station protection as simple as possible. It is, as yet, impossible to define what this should be.

20. If a full measure of line protection is added, such as overhead grounded wires, the stations will, in turn, be much relieved.

General.

21. Further and fuller data are required on the following:

a. Amount of direct stroke actually encountered on transmission lines.

b. Magnitude of bound charge possible on any given line—graded according to design—voltage.

c. Effect of line impedance to travel of static disturbance.

d. Corroborative data of the effectiveness of overhead grounded wires.

e. The relative value of overhead grounded wire for wood pole lines of short spans as against steel-tower lines of long spans.

f. Best relative position between overhead grounded wire and line wires.

g. Relative value of one, two, or three, etc., grounded wires.

h. Best relative position for lightning-rods.

i. Action of insulators under direct stroke.

k. Equivalent spark gap of high-tension insulators.

l. Relations between shunt resistance and given opening of horn gap.

m. Nature of line-to-line disturbances on very high voltage systems.

n. Equivalent spark gap of line choke-coils and consequent protective power.

APPENDIX

LIGHTNING PERFORMANCE DATA, SEASON 1907. PRESUMPSCOT ELECTRIC COMPANY, WESTBROOK, MAINE

Summary.

Length of record, approximately, 26 weeks, June to December, 1907.

Number of changes to tell-tale papers 30 complete.
4 part changes (local).

Attending circumstances	Lightning	Clear*	Switching	Grounds and short circuits	Total
Number times disturbance occurred to lightning protective apparatus........	10	9	2	4	25

* Includes all other weather but lightning; causes not known, usually light discharges over some isolated unit; for example, phase to phase.

Distribution of Operation.

Two-phase. 2300 volts. Lightning protective apparatus.

Date	Line to ground %		Phase to phase %	
	Total = 18 paths		Total = 9 paths	
6/23-26		22.2		22.2
	Total = 22 paths		Total = 11 paths	
6/26-27		72.6		45.4
7/21-27		9.08		11.1
7/27-8/3		4.54		11.1
Average—per wk. for 26 weeks		4.18		3.45
" per disturbance....	(4)	27.11	(4)	22.45

NOTE: Figures given equal percentage of total protective apparatus paths operating.

Three-phase. 11,000 volts. Lightning protective apparatus.

Date	Line to ground %		Line to line %	
	Total (paths) = 33		Total = 15	
6/18-19	"	9.1		46.6
6/23-26	" = 39	48.8		87.
6/26-27	" = 33	54.8		73.2
7/7 - 8	" = 39	33.3		46.7
7/8 - 9		59.1		33.3
7/14-21		7.7		20.0
7/21-28	" = 42	40.4	" = 18	77.8
7/28-8/4		71.5		94.6
8/25-9/1				11.1
9/1 -15				11.1
9/15-22		14.3		33.3
9/22-29		50.0		78.0
9/30-10/6		2.38	" = 15	40.0
10/6 -13			" = 18	11.1
10/20-27				16.7
10/27-11/3		4.76		11.1
11/3 -10		9.52		50.0
12/1 - 8				5.55
12/8 -15	Special by switching	35.8	" = 12	75.0
Average per wk. for 26 wks.		17.0		31.7
Average per disturbance	(14)	31.5	(19)	43.3

NOTE: Figures given equal percentage of total protective apparatus discharge paths operating.

Prominent characteristics brought out.

1. Line-to-line disturbances pronounced, and of greater frequency than line-to-ground disturbances.

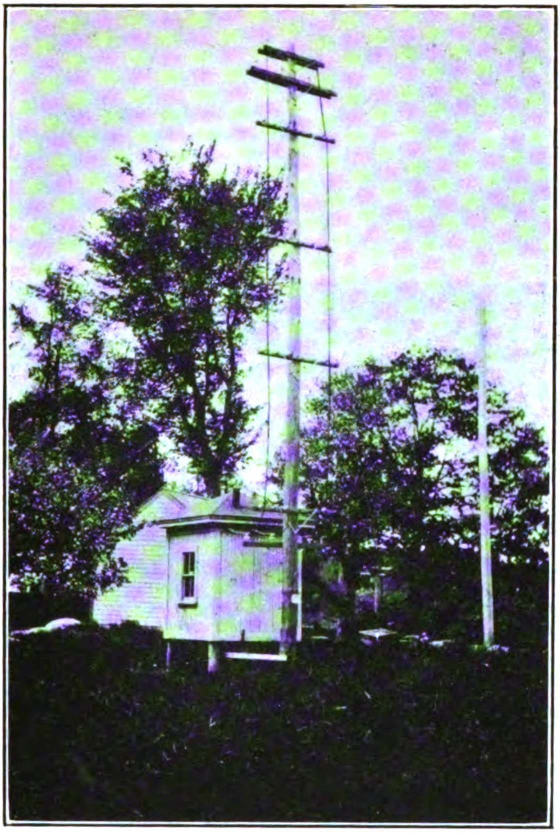
2. Line-to-ground, freer over fuses in shunt to low-equivalent, but this does not prevent the low equivalent operating at the same time.

3. Circuit-breakers set too light, objectionable; open on blowing of fuses, disturbing the balance of the system, and then frequently causing a loss of power while stations are getting into synchronism again.

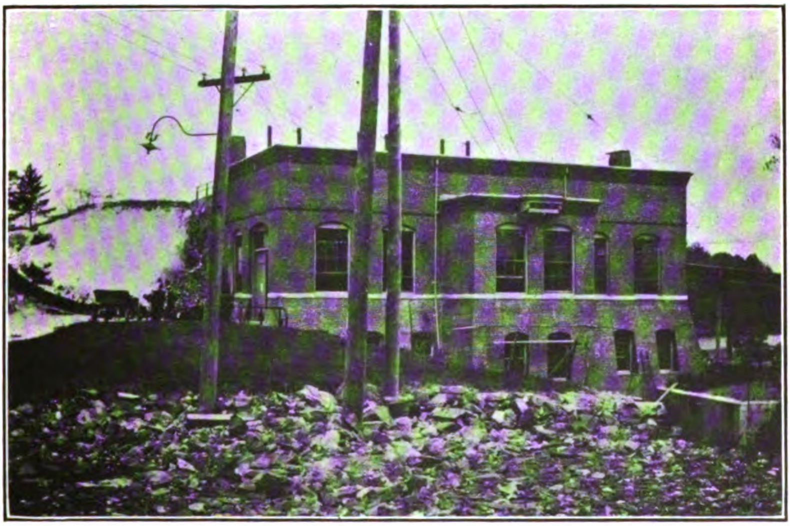
Operation of power plants.

The Presumpscot Electric Company is not always able to operate to the best advantage electrically, because of the conditions which obtain. In the first place, the flow of water must be maintained primarily for the interest of the direct development of the mill at Cumberland Mills. Again, all the hydroelectric stations are on the same river, and while the flow of this is controlled, the company must, of course, protect the other users on the river. This introduces another variable. Furthermore, the supply of water to Saccarappa and Smelt Hill stations is affected by the run-off from the territory between the lake and the sea on which the streams are not ponded. It becomes evident, then, that during heavy rains, or in the spring, when there is a large amount of side-stream water, the flow from the lake may be well cut back, and Eel Weir is then unable to furnish its full supply. On the other hand, if the electric station below calls for water, more water must be run through the Eel Weir station than is desirable. In order to furnish a uniform flow at Cumberland Mills, it is sometimes necessary to store in the Saccarappa pond, and again to sluice, thus producing a variable head.

There are a number of other conditions which have a greater or less effect upon the system, and it is to harmonize all these that the company maintains turbo-generators, always having one floating on the line prepared to make good any little deficiencies, and the other two are usually warmed up ready to run, so that whatever the demands of the paper mill, they can be met up to the limit of the water power at that moment available, plus the turbine. If the load exceeds that, steam engines must then be substituted for motors on some of the large groups in the mill.

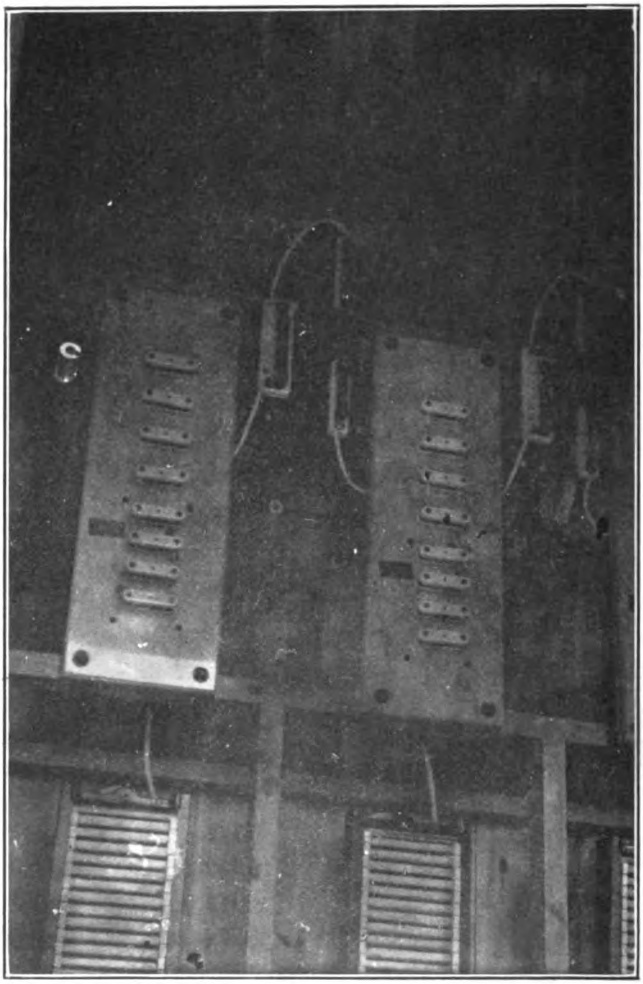


Presumpscot Electric Co. View of Eel Wier Half-way Line Lightning Arrester House



Presumpscot Electric Co. Eel Wier Falls Power Station

Just above basement windows, over the tail race, special ground connections of broad copper straps may be seen. These lead off in two separate directions to additional grounds in order to assure good operation of the protective apparatus. The original ground is the tail race



Presumpscot Electric Co. Interior of Eel Wier
Half-way Line Lightning Arrester House

A paper to be presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N.J., June, 29-July 2, 1908.

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MODERN DEVELOPMENT IN SINGLE-PHASE GENERATORS

BY W. L. WATERS

The single-phase alternator has been in commercial use now for twenty years and it may seem surprising that there should be new developments at this late date. However, single-phase alternators have been used in the past almost exclusively for lighting work, and in units of comparatively small output and low speed. Recently, on account of the adoption of single-phase current for traction work, an important demand has arisen for large high-speed, low-frequency, single-phase generators. It is in the design and manufacture of such units that the engineer has had to overcome new difficulties. In large, high-speed, single-phase generators for 15 and 25 cycles the difficulties met with are due almost entirely to the large pole-pitch and high armature reaction which it is necessary to adopt. A 500-kw., 60-cycle, 72-pole, single-phase generator would have a pole-pitch of about 7 in., while a 6000-kw., 15-cycle, 2-pole machine would have one machine of about 120 in. It is easily seen that the design of these will be radically different.

These difficulties in single-phase generators of large pole-pitch are the result of:

1. Pulsation of the armature reaction.
2. Mechanical stresses on the end-connections of the armature coils.

The pulsation of the armature reaction causes hysteresis and eddy-current losses throughout the machine, often resulting in dangerous heating and low efficiency. The mechanical stresses due to the current in the ends of the armature coils result in vibration and distortion of the windings, and often in damage to the insulation or complete destruction of the coils, these stresses being particularly serious in single-phase railway generators, on account of the sudden variations in load and numerous short-circuits to which these machines are subjected. As the effect of the mechanical stresses on the armature coils, and the losses due to the pulsation of armature reaction, practically increase proportionally to the square of the pole-pitch in generators of standard design, it is easily seen why these effects which were negligible in the old single-phase alternators of small pole-pitch have become quite serious in the modern turbine-driven generator. The seriousness of these difficulties when they were first met with was so great that even within the last two years responsible engineers have stated it was impossible to build satisfactory low-frequency, high-speed, single-phase generators of large capacity, and it is only by careful study and experimenting that the modern machine of this type has been developed.

Losses due to pulsation of armature reaction. In a polyphase generator the armature current produces a magnetic flux which rotates synchronously with the field magnet. This magnetic flux being of practically constant magnitude, causes very little loss in the iron of the magnetic circuit. On the other hand, the armature current in a single-phase generator produces a pulsating magnetic flux which is stationary in space. It is easily seen that this pulsating flux will cause hysteresis and eddy-current losses throughout the whole magnetic circuit. The exact effect of the armature reaction flux on the rotating magnets depends, of course, on the relative phase of the armature current and electromotive force; that is, on the power-factor of the load on the generator. When the power-factor is unity and the armature current is in phase with the electromotive force, the armature reaction flux is a cross-magnetization; when the power-factor is zero and the armature current is 90° out of phase with the electromotive force, the armature reaction flux is a demagnetization. In the special case in which the rotating field magnet is cylindrical, without projecting poles, the effect of the armature reaction flux on the magnets is, of course, more nearly independent of the power-factor of the armature current. But in any case this flux is a pulsating one, and there are important losses in the field magnets, due to their rotation through this pulsating cross-flux or demagnetization flux.

An estimate of the combined losses in the armature and field magnets due to the pulsating armature reaction can be obtained in a number of ways. We can measure the increase of the power required to rotate the field magnets due to normal root-mean square current in the armature coils, with:

1. Direct current in the armature.
2. Alternating current of synchronous frequency in the armature.
3. Armature short-circuited and field excited.

Or with the magnets stationary we can:

4. Send normal frequency alternating current through the armature and measure the losses by a wattmeter.

These methods must all be regarded as convenient tests which are found by experience to give a good indication of the magnitude of the losses. Method (4) has the additional advantage that we can vary the relative position of the armature reaction flux and the pole faces, and thus investigate the variation of the losses in a single-phase generator with the power-factor of the load.

The only exact methods of measuring the losses are:

1. As unknown losses in a motor-generator-method efficiency test, or
2. From a comparison of the temperature rise obtained on full load with that obtained with known losses.

Unfortunately, both of these tests are difficult to make accurately, especially on a large machine, and probably in practice they do not give results which are any more accurate than the other methods. So at the present time we have to acknowledge that though we know a great deal about the relative values of the losses under various conditions, our knowledge of their absolute values are only approximate.

Pole-face dampers. Losses caused by a pulsating flux in the magnetic circuits are due to:

1. Hysteresis.
2. Eddy currents.

And the relative magnitudes of the two depend on the amount of solid metal in the path of the flux. If the whole magnetic circuit is laminated, then the losses are practically all due to hysteresis. On the other hand, if we have solid cast-steel poles there will be eddy currents in these poles which will partly choke back the pulsation of the flux and the hysteresis loss will be reduced. But in this case there will be eddy-current losses in addition to the hysteresis, and the way in which the total loss is changed will depend on the proportions and design of the magnetic circuit. If we place a heavy copper damper in the path of the pulsating flux, this will provide a low-resistance path for the eddy currents, and the pulsating flux, and consequent hysteresis loss, will be reduced practically to zero, while on account of the low resistance of the damper circuit the eddy loss will not be appreciable. The way in which the losses and the pulsating flux vary according to the presence of eddy currents can be determined for any particular design by changing the thickness of the laminations, or changing to solid poles or dampers. It is usually found that the losses are greatest with heavy laminations or solid poles; that they are less for thin laminations, and practically zero when heavy low-resistance dampers are used either with solid or laminated poles.

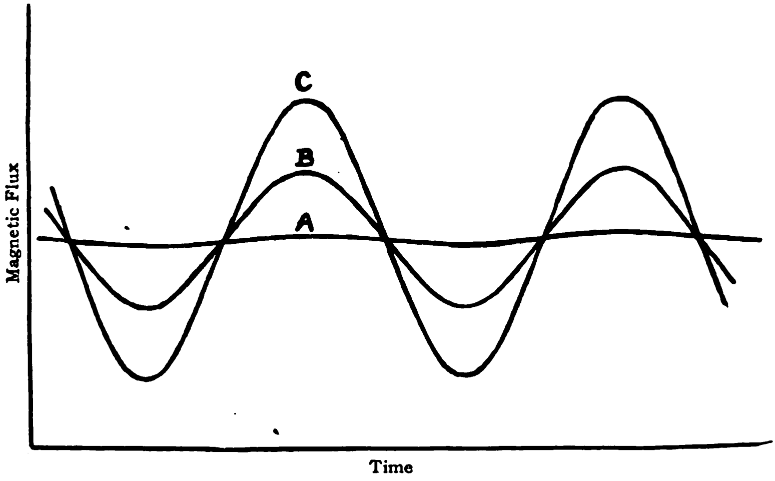

FIG. 1

Fig. 1 shows the pulsation of the armature reaction flux in a 500-kw., single-phase, 20-pole generator, as determined by means of search-coils wound on the pole-faces. "*C*" shows the pulsation for laminated poles, No. 29 gauge: "*B*" shows the same machine with solid poles: "*A*" shows the same solid pole faces covered with a ⅜-in. copper plate. The magnitude of the pulsations in the three cases is about in the ratio of from 30 to 15 to 1; thus the copper plate has practically damped out all pulsations, the armature reaction flux becoming constant. In practice, a copper damper usually takes a form similar to the squirrel-cage secondary of an induction motor. Heavy copper bars are dovetailed into the pole faces, and short-circuited at the ends by copper rings or discs. Fig. 2 shows such a cage damper on the field magnet of a 6000-kw., 2-pole generator.

The question of losses due to the pulsating armature reaction in a single-phase generator may be considered in another and possibly a simpler way. The single-phase pulsating field is equivalent to, and produces the same effect as, two rotating fields each of half its maximum value, one rotating at the same speed and in the same direction as the generator field magnet, and the other rotating at the same speed but in the opposite direction. The flux rotating synchronously with the field magnet, being constant in magnitude, causes very little loss. The flux rotating in the reverse direction causes losses throughout the whole magnetic circuit due to hysteresis and eddies. If we have a squirrel-cage damper enclosing the field magnets, this damper system acts in regard to this reverse rotating flux in the same way as the short-circuited secondary of an induction motor or transformer, a current is induced in the damper which produces a field that neutralizes the rotating flux. The eddy and hysteresis loss in the iron of the magnetic circuit which would be caused by this rotating flux is thus eliminated, and the only loss is that due to the current circulating in the damper. If we make the conductors forming the squirrel cage of sufficiently low resistance, this damper loss becomes negligible, with the result that the entire loss due to the pulsating armature reaction of the single-phase generator is practically eliminated.

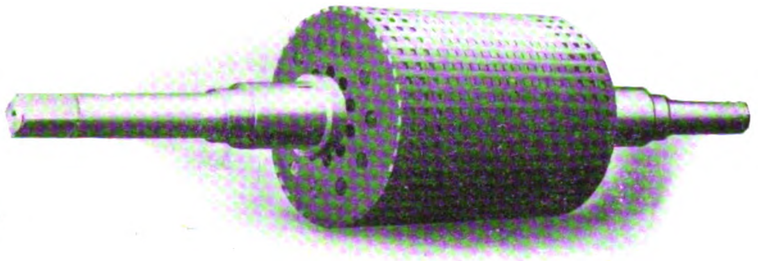

FIG. 2

To show how serious this matter of losses becomes in two-pole single-phase machines without dampers, the following table is given, showing the losses and full-load temperature rises on three turbo-generators, both with and without dampers:

TWO-POLE, 25-CYCLE, SINGLE-PHASE GENERATORS. SAME CURRENT PER ARMATURE CONDUCTOR ONE AND THREE-PHASE UNDER ALL CONDITIONS AND ALL LOSSES IN PER CENT. OF SINGLE-PHASE RATING

		Three phase		Single phase			
Size	Type field	Without dampers		Without dampers		With dampers	
		Loss	Temperature	Loss	temp.	Loss	temp.
750 kw.	Solid	0.53	27°c.	3.75	95°c.	0.8	34°c.
1000 kw.	Solid	0.3	31°c.	3.0	122°c.	0.5	37°c.
1000 kw	Laminated	0.2	19°c.	3.8	150°c.	0.3	18°c

It will be seen that in these three machines, operating single-phase, there is due to the pulsating flux an average loss of 3.5% and an average temperature rise of 125° cent., without dampers; with dampers the average loss is 0.5% and the temperature rise 30° cent. Figures are given only on comparatively small machines on account of the difficulty of measuring losses on large machines. But tests on larger generators up to 6000-kw. capacity show that the improvement due to heavy copper dampers is even more striking in large machines than it is in small. So far as experience goes at the present time, it may be said that the use of such dampers is the complete solution of the difficulties due to pulsating armature reaction met with in large, low-frequency, two-pole, single-phase generators.

Mechanical stresses on armature coils. That it was necessary mechanically to brace the end-connections of the armature coils on a direct-current machine subjected to sudden loads and short-circuits has been known for many years. But until quite recently additional supports for alternator armature coils were seldom provided. The reason for this was that as the continuous short-circuit current of an alternator is only about two or three times normal, it was not considered that the mechanical stresses on the ends of the small pole-pitch coils generally in use were sufficiently great to cause any trouble. Only during the last few years has it been demonstrated by experience that coil supports on large pole-pitch alternators are not only advisable but necessary, and that on account of the numerous short-circuits, they are particularly necessary on single-phase machines operating on traction circuits.

When an alternator is suddenly short-circuited, the first rush of current is limited only by the self-induction in circuit. In the case of an alternator of very low self-induction, this first rush of current on sudden short-circuit will be 15 or 20 times normal full-load current. As the mechanical stress on the end-connections varies as the square of the current, this means that the stress on the armature coils is 200 to 400 times normal. A 6000-kw., 2-pole, 25-cycle, single-phase generator will have a pole pitch of about 100 in., and the length of the end-connection at one end of one armature coil will be about 180 in. We find that the mechanical stresses on the end-connections at one end of one armature coil of this machine on a sudden short-circuit is something like five tons; and we usually find that on low-frequency high-speed generators of large capacity the mechanical stresses on the end-connections at one end of one armature coil on sudden short-circuits are from 2 to 10 tons. When we consider that this comes as a sudden mechanical shock on the winding, we can realize the kind of coil supports that are required, and can understand the disastrous results sometimes obtained on short-circuits, when such supports are omitted.

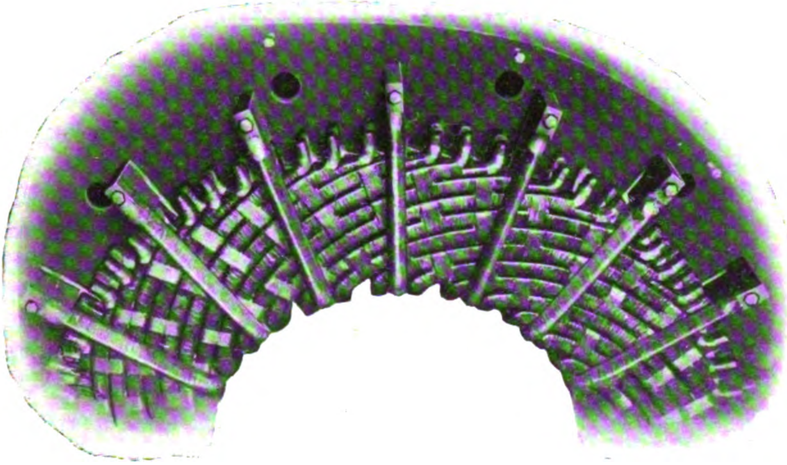

FIG. 3

We can see from these stresses that coil supports must be of metal of heavy cross-section. The objections to metal are, of course, those of insulation, but though coil supports of wood, porcelain, and similar insulating materials have been tried, it is easily understood that they have proved unsatisfactory on machines of large pole pitch. Fig. 3 shows a form of coil support which has been developed and proved satisfactory. It is of bronze and of heavy girder, section and insulated for the full generator voltage. The coil support and its method of application are evident from the illustration; it is placed in position after the machine is wound and is removable in a few minutes at any time. It is not suggested that this is the only satisfactory type of coil support that can be used; it is given as a type which has proved successful in actual operation on machines up to 10,000-kw. capacity, and it has apparently solved the difficulties due to mechanical stresses on the end-connections of large pole-pitch generators which are liable to sudden variations in load and frequent short-circuits.

The two main difficulties met with in large low-frequency, high-speed, single-phase generators, which have been described above, can at the present time be regarded as having been successfully overcome. The use of heavy copper dampers on the pole faces and heavy bronze coil supports applied to the ends of the armature coils in such a way as to take directly the mechanical stresses which develop on short circuits, have now made such machines a practical success. Like every other new type of electrical machinery, the large turbine-driven, single-phase generator has had to go through a period of development, but at the present time it may be said that such generators for 15 and 25 cycle, and in units of 5000 to 10,000 kw. capacity can be, and are, built with the same success as that obtained on standard slow-speed polyphase generators.

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THE DETERMINATION OF THE ECONOMIC LOCATION OF SUB-STATIONS IN ELECTRIC RAILWAYS

BY GERARD B. WERNER

The method of attacking the problem of the location of sub-stations in electric railways is governed by the physical layout of the road. The problem involved in the case of networks serving a limited territory, such as urban or suburban lines, may be solved from a study of the magnitude of the various relatively fixed load-centers which are created by the configuration of the lines; and the sub-stations may be placed at the different centroids of the system. In the case of long single roads connecting distant communities, such as interurban and trunk lines, there is presented the study of more or less uniformly loaded stretches, in which there are no distinct centers of load, except those that result from the characteristics of the line profile or the traffic movement. The latter problem is more susceptible to mathematical treatment, so that the contents of this paper will be confined to the consideration of interurban and trunk line projects, or, in other words, to relatively long roads.

Of the various considerations that govern the layout of the secondary distribution of electric railways, the question of economy is generally the preponderant influence. It is obvious that the economic condition should be determined as a basis of reference, and approximated as far as is consistent by the actual design. The theoretical economic solution, however, may be difficult or impossible of attainment, if certain operating considerations of a mechanical or an electrical nature intervene and dictate the use of a cross-section of secondary copper other than that determined by Kelvin's law. For example, the economic drop may exceed the limiting drop permitted for the acceleration of the motors, under which conditions economy would give precedence to regulation. In the present problem, as will appear shortly, for a given mean square current per car, a given cost of copper, and a given unit cost of energy, the drop, according to Kelvin's law, is inversely proportional to the square root of the number of annual car-hours. The cross-section of the secondary copper is, therefore, dependent on the number of cars or trains in service, the length of line, and the schedule speeds. Thus for infrequent service, the economic drop may be excessive and result in stalling the cars; similarly, for dense traffic movements, the economic drop may be insufficient and render the resulting investment prohibitive. Kelvin's law is based on the mean power lost, while the operating criterion is based on the maximum drop.

Besides these technical considerations, which may be decisive in the design of the distributing copper, a number of commercial considerations exert a pronounced influence on the location of the sub-stations. In this category may be included the question of placing the sub-station at or near a railway station, in order to utilize the station employes for emergency switchboard operation, or to provide accessibility for periodical inspection, in the absence of continuous attendance. Thus, the sub-station may be somewhat removed from the site determined by purely economic reasons.

The specific purpose of this paper is to develop an equation for the number of sub-stations, or the distance between sub-stations, which will render the total annual charges on the installation a minimum. This equation is to be in terms of the various constants fixed by the length of line, time-table, the weight of cars or trains, the motor characteristics, the cost of energy, and the equipment charges.

The initial step in the treatment of this problem is the determination of the analytical expressions of the various annual charges as functions of a single variable, the number of sub-stations. All those items of the annual charges which may be regarded as constant and independent of the number of sub-stations, may be omitted in the analysis. Thus, assuming that it is not necessary to feed the sub-stations with separate high-tension lines, the weight of copper and the losses in the primary distribution are dependent only on the energy to be transmitted and the mean distance, so that the primary transmission may be eliminated from consideration. Obviously, the charges on the trolley suspension and insulation do not enter. The following algebraic expressions are therefore required:

1. Annual charges on sub-stations,
2. Annual charges on overhead copper,
3. Annual cost of sub-station losses,
4. Annual cost of secondary conductor losses.

These four items are present whether the system employed is continuous, single-phase, or three-phase current. For the purposes of this paper, it will be sufficient to develop the formula for the simplest layout. The single-phase system has been elected, therefore, to illustrate the general method of deducing the equation, although by the introduction of the proper modifications in the analytical expressions (to cover such features as the third-rail, synchronous converters, attendance, etc., in the continuous-current system, and the two overhead conductors, three-phase transformation, etc., in the three-phase system) the results of this analysis will be equally applicable to all.

Annual charges on sub-stations. The first point to be determined is the sub-station capacity. In general, if a line contemplates electrification we may assume that the frequency of the various traffic movements dictated by the present or prospective time-table results in a more or less uniformly distributed load along the line, and consequently the load between adjacent sub-stations varies more or less directly with the length of the sub-station section. Thus, neglecting for the moment the question of reserve, the capacity of each sub-station will be proportional to the distance between sub-stations, the aggregate sub-station capacity remaining constant, and being governed by the total maximum load occurring on the line at one time.

In those classes of service where the traffic density through the varying exigencies of the train-weights, time-table, or profile, is not uniform along the entire line, it is necessary to consider individual *load-sections* rather than general *distance-sections*. When this condition exists, the line may be broken up into divisions where the load per mile is approximately constant, each particular division segregated, and treated separately for the determination of the sub-station capacity and the distance between sub-stations.

The question of spare capacity is influenced by the kind of transformation between the transmission and the distribution.

A three-phase primary may be incumbent on account of one or more of the following reasons: 1. The railroad may desire to sell surplus power to various industrial establishments where single-phase current is not acceptable. 2. The additional cost of single-phase generation may not offset the advantages accruing from the simplicity of the switching gear. 3. The railroad may, from compelling commercial reasons, desire to purchase its power from an outside company.

With a three-phase primary transmission we are practically limited to two methods of transformation to the secondary distribution. 1. Sub-stations transforming to single phase and feeding successive sections with separate phases, or 2, sub-stations transforming to two-phase and feeding adjacent sections with either phase. In the first case, two transformers are required in each sub-station, so that the same phase may be supplied to the common section extending between them. In the second case, two transformers are also required, so that the sub-station capacity will be divided between at least two units, with a possible third as a spare unit.

With the assumption made above of the uniformity of the distribution of load along the line either (*a*) for the entire stretch between terminal, or (*b*) for the particular load-section in question, and further assuming that the transformers are capable of withstanding momentary overloads of 150 per cent., the following expression results:

$$KW = \frac{0.4\,P\,(1+q)}{s} \tag{1}$$

where

KW = required capacity of one sub-station in kilowatts,

P = total maximum power input in kilowatts required at one time on the line,

q = spare capacity in terms of the capacity actually required

s = number of sub-stations

One transformer will have a capacity of

$$KW' = \frac{0.2\,P}{s} \tag{2}$$

The cost of a single sub-station consists of the cost of real estate (building and ground) which may be taken as independent of the capacity, and the cost of equipment, which is a function of the capacity. The equipment cost comprises the cost of transformers, switchboard, wiring and protective apparatus. The cost of the transformers for a given type, voltage and frequency in sizes between 150 kw. and 500 kw. may be taken as a linear function of the output as follows:

$$F_t = 2\,(K_1 + K_2\,K\,W')\,(1+q) \qquad (3)$$

where K_1 and K_2 are constants fixed by the manufacturer.

The remainder of the equipment may be grouped as auxiliary, and, without appreciable error, taken at a fixed constant value irrespective of the kilowatt capacity. If it is further assumed that one average fixed charge will uniformly cover the different equipment items, and another the building and ground, the annual charges on the total sub-stations may be written down:

$$a_s = s\left[f_r\,F_r + f_e\,\left\{\,F_a + (1+q)\left(2\,K_1 + \frac{0.4\,K_2\,P}{s}\right)\right\}\,\right] \qquad (4)$$

in which

F_r = cost of building and ground
F_a = cost of switchboard, wiring, protective apparatus, etc.
f_r = fixed charges on building and ground as decimal
f_e = fixed charges on equipment as decimal

or, putting,

$$M_1 = f_r\,F_r + f_e\,\{F_a + (1+q)\,2\,K_1\} \qquad (5)$$

and

$$M_2 = f_e\,(1+q)\,0.4\,K_2\,P \qquad (6)$$

$$a_s = M_1 s + M_2 \qquad (7)$$

Annual charges on overhead copper. The overhead conductors may be proportioned according to Kelvin's law, if the losses therein can be computed without too much labor. To this end it is consistent to assume that the mean load on each sub-station is fixed at a certain distance, one-third of the length of the section, from the sub-station. Since the cross-section of the copper by Kelvin's law, for a given transmitted power, depends only on the cost of copper and the cost of the energy, the trolley can be determined for the economic condition independent of the distance that the power is transmitted from the sub-station to the car or train. However the cost of copper becomes a function of the distance between sub-stations through the fact that the losses in the overhead conductors per section vary as the car-hours per section or inversely as the number of sub-stations.

Letting

w = root of mean square load per car or train in apparent watts

v = trolley voltage

h = car or locomotive hours per year

s = number of sub-stations

r = resistance per mile of trolley wire

$D = T/s$ = length of one section in miles, the end-sections being one-half the length of the others.

T = total length of line in miles

k = cost of one kilowatt-hour at high-tension side of sub-station in dollars

ε = per cent. all-day efficiency of sub-stations

F_c = cost of copper in cents per pound

f_c = annual charges on copper as decimal

the following expression of Kelvin's law results:

$$\frac{w^2 h D k r}{v^2 1000 \times 3 s \varepsilon} = \frac{876 D F_c f_c}{r 100} \tag{8}$$

the first member representing the annual cost of the energy lost section, and the second member the annual charges on the investment.

Solving for r, to obtain the cross-section of copper,

$$r = \frac{162 v}{w} \times \sqrt{\frac{F_c f_c s \varepsilon}{h k}} \tag{9}$$

Substituting in the preceding equation the value for r, we obtain the total annual charges on the overhead conductors,

$$a_c = \frac{8.76 \times D F_c f_c s}{\frac{162 v}{w} \times \sqrt{\frac{F_c f_c h k}{s \varepsilon}}} \tag{10}$$

or

$$a_c = \frac{0.0541\ T\,w}{v} \times \sqrt{\frac{F_c\,f_c\,h\,k}{s\,\varepsilon}} \tag{11}$$

or, placing

$$M_s = \frac{0.0541\ T\,w}{v} \times \sqrt{\frac{F_c\,f_c\,h\,k}{\varepsilon}} \tag{12}$$

$$a_c = \frac{M_s}{\sqrt{s}} \tag{13}$$

Annual cost of sub-station losses. Reverting again to the premises of the practical uniformity of line loading and the equal distribution of the total sub-station capacity along the line, it is apparent that under the assumption that the per cent. of iron and copper losses is constant for all sizes of transformers under consideration, the transformation of the given amount of energy required at the overhead conductor will entail transformer losses that will be constant and independent of the capacity or number of the individual sub-stations.

As a corollary to this conclusion, the sub-station all-day efficiency will be the same irrespective of the spacing of the stations. The error accruing from the assumption of constant transformer losses is almost negligible, and, furthermore, the omission of the cost of sub-station losses simplifies the algebraic operations in the determination of the condition for the minimum annual charges.

Annual cost of secondary conductor losses. The annual cost of the losses occurring in the overhead copper was computed from the expression of Kelvin's law. The secondary conductor losses should contain, to be rigorously exact, the losses occurring in the track-return, but the calculations show that these amount to only a small per cent. of the total yearly cost. This is readily seen from a comparison of the trolley and track resistances. To take the most unfavorable combination likely to occur in practice, assume an overhead wire of No. 0000 and 60-lb. rails. The ratio of track resistance to trolley resistance is 0.0422 : 0.259, or 0.163. To take the most favorable combination, No. 00 wire and 100-lb. rails, the ratio is 0.0253 : 0.412, or 0.0615. So that the track losses lie between about 6% and 16% of the copper losses.

The track losses will take a form similar to the first member of equation (8), all the factors entering being constants except the car-hours per section, and, as will appear farther on, the retention of a term with s in the denominator will render the expression $d\,a/d\,s$ an equation of the third degree. The resulting value of s, after the algebraic solution, would be rather cumbersome to evaluate from the numerical constants, and the sacrifice of mathematical precision will not materially vitiate the practical result.

Solution. With the algebraic expressions for the several items constituting the total annual charges on the sub-station and overhead copper investments, we may proceed with the solution. The total annual charges,

$$a = a_s + a_c + a_c \tag{14}$$

since the annual charges on the copper are equal to the annual cost of the losses.

$$a = s\left[f_r F_r + f_c \left\{ F_a + (1+q)\left(2\,K_1 + \frac{0.4\,K_2\,P}{s}\right)\right\}\right] + 2\left[\frac{0.0541\;T\,w}{v} \times \sqrt{\frac{F_c\,f_c\,h\,k}{s\,\varepsilon}}\right] \tag{15}$$

Or, using the corresponding expressions,

$$a = M_1\,s + M_2 + 2\,\frac{M_3}{\sqrt{s}} \tag{16}$$

From this equation it is seen that the curve of the total annual charges is the result of a curve superposed on a straight line. Differentiating,

$$\frac{da}{ds} = M_1 - M_3\,s^{-\frac{3}{2}} \tag{17}$$

Placing the differential equal to zero and solving for s

$$s^{\frac{3}{2}} = \frac{M_3}{M_1} \tag{18}$$

or

$$\log s = 0.667\,(\log M_3 - \log M_1) \tag{19}$$

Hence

$$\log D = \log T/s = \log T - 0.667\,(\log M_3 - \log M_1) \tag{20}$$

It will be seen on inspection that $\frac{d^2 a}{d s^2}$ will be greater than zero, so that the value of s given in equation (19) will render a a minimum.

The equation $\frac{d a}{d s}$ when multiplied through by s, shows that *for a minimum value of the annual charges, the cost of copper is equal to that part of the cost of the sub-stations which is independent of the output.*

Example: To illustrate the use of this equation, there is submitted herewith a certain interurban railway project. The line is single-tracked, 110 miles in length laid with 80-lb. rails. The traffic is a mixed passenger and freight, the former being handled by 40-ton motor cars, and the latter by 60-ton locomotives. The preliminary study of the calculated run-sheets shows the following:

Service	No.	Weight tons	Schedule speed m.p.h.	Train hours per day	Average kilowatt input
Through freight	2	960	15	14.6	275
Local freight	4	480	21	21.0	221
Express passenger	8	40	40	22.0	104
Local passenger	16	40	32	55.0	97
Baggage	4	50	34	12.9	120

Total train-hours per day, 126.
Average apparent kilowatt input per train, 176.

The energy is transmitted from a power company's plant at 66,000 volts, and is transformed to 3300 volts at the sub-stations, where it is sold to the railway company at the rate of one cent per kilowatt-hour.

The cost of each sub-station building and ground was estimated uniformly at $2000, the cost of the switchboard, wiring, and protective apparatus at $1800 per sub-station, the price of copper at 15 cents per pound, and the fixed charges on these three items at 7 per cent., 15 per cent., and 8 per cent., respectively. The cost of oil-insulated self-cooling transformers in sizes of 150 kw. to 500 kw. for 25 cycles 60,000 to 3,300 volts was found to be

$$F_t{}^1 = 1080 + 2.9\, K W'$$

Hence the following numerical values result:

$$\begin{aligned}
f_r &= 0.07\\
F_r &= 2000\\
f_e &= 0.15\\
F_a &= 1800\\
K_1 &= 1080\\
T &= 110\\
w &= 176,000\\
v &= 3300\\
F_c &= 15\\
f_c &= 0.08\\
h &= 46000\\
k &= 0.01\\
\varepsilon &= 0.96
\end{aligned}$$

Then, assuming that there will be no spare transformers,

$$M_1 = 140+594 = 734$$

$$M_s = \frac{0.0541\times 110\times 176000}{3300}\times\sqrt{\frac{15\times 0.08\times 46000\times 0.01}{0.96}}$$

$$\begin{aligned}
M_s &= 317\times 24.0 = 7608\\
\log\ M_s &= 3.8813\\
\log\ M_1 &= \begin{array}{r}2.8657\\ \hline 1.0156\end{array}\\
\log\ s &= 0.6771\\
s &= 4.754
\end{aligned}$$

which indicates that the economic condition would be about 5 sub-stations about 22 miles apart.

The required trolley section has a resistance,

$$r = \frac{162\times 3300}{176000}\times\sqrt{\frac{15\times 0.08\times 5\times 0.96}{46000\times 0.01}}$$

$$\begin{aligned}
r &= 3.04\times 0.1118 = 0.34 \text{ ohms per mile}\\
r' &= 0.0643 \text{ ohm per 1000 ft.}
\end{aligned}$$

which corresponds to a No. 000 wire.

Having established the number of sub-stations and the cross-section of the overhead conductor, it remains to be seen whether the consequent drop between the sub-station and the train is prohibitive. The graphic time-table shows that the maximum number of trains on the line simultaneously is as follows: one through freight, two local freights, eight passenger cars, and two baggage cars. With these trains in the most unfavorable position likely to occur, the total peak load is about 3700 kw. and the maximum input required between sub-stations is 1020 apparent kilowatts.

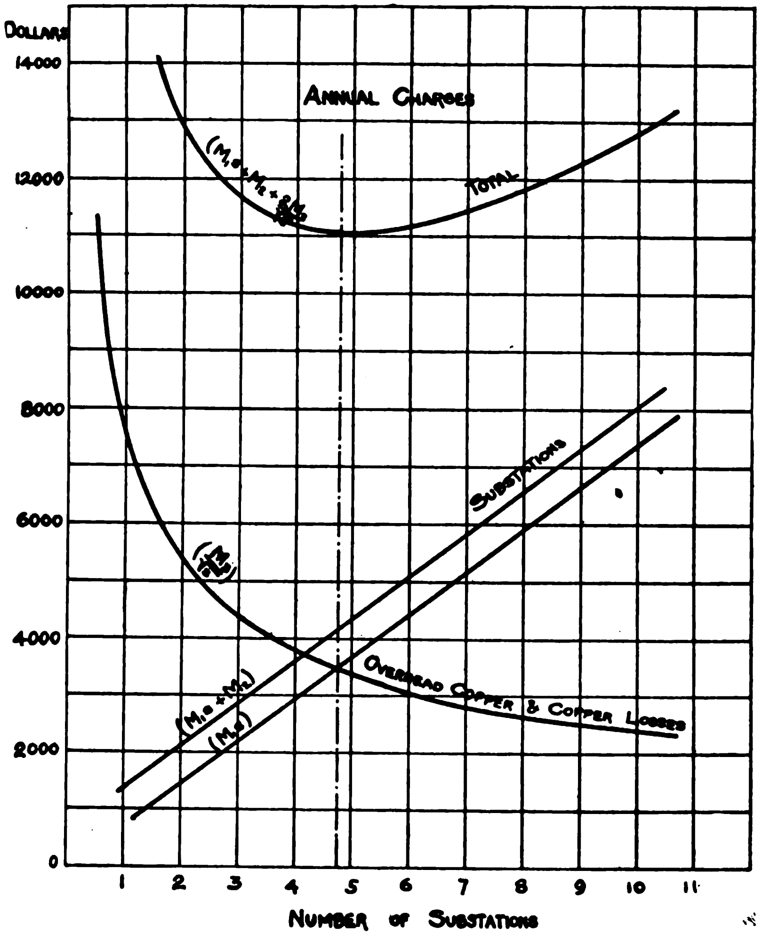

Fig. 1

Assuming that this load is at the maximum distance from the sub-station, a single catenary construction and 80-lb. rails with a total drop (ohmic and inductive) of 11.7 volts per 100 amperes per 1000 ft. will give a momentary voltage-drop of

$$\frac{1020000\times 11.7\times 5.28\times 22}{2\times 3300\times 100\times 2} = 1050 \text{ volts}$$

or 32 per cent., which would be permissible, although it is somewhat beyond the usual working limit of 25 per cent.

With the numerical constants determined for the present problem, the loci of equations (7), (13), and (16) have been plotted in Fig. 1. These curves, within the approximations previously noted, represent the annual charges on the several items of the distribution. It will be seen that the lowest point of the curve of the total charge corresponds to that number of sub-stations at which the curve of sub-station charges (M_1s) crosses the curve of charges on the secondary copper.

Conclusion. It is readily appreciated that certain approximations in the analytical expressions that make up the annual charges on the installation are of no great practical consequence. The introduction of complicated expressions would not enhance the accuracy of the actual result, since it is rarely possible to evaluate s into a whole number, to happen across a commercial transformer of the exact rating calculated, or to make the theoretical cross-section of the secondary copper conform exactly to the commercial sizes available for trolley wires and feeders. The combined influence of these considerations may more than offset the nicety attained by a more rigorous solution.

The use of the above formula for determining the economic location of sub-stations in single-phase railways constitutes a method which will obviate the necessity generally incumbent of solution by trial. The solution for the economic number of sub-stations, or the economic distance between adjacent sub-stations, is expressed in terms of those constants which are already available from the previous technical and commercial study of the service requirements. These numerical constants are evaluated for the particular problem at hand, and hence establish, within the scope of electric railroading problems defined at the beginning of this paper, the generality of the formula deduced.

A paper to be presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., June 29-July 2, 1908.

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(*Subject to final revision for the Transactions.*)

CONDUCTOR RAIL MEASUREMENTS

BY S. B. FORTENBAUGH

General. The Underground Electric Railways Company of London, Ltd., control and operate electrically the Metropolitan District Railway and contingent lines, 56 miles of main-line double track, and three deep level " tube " railways, with connections, aggregating approximately 28 miles of double track. A detailed description of the electrification of the system, by the writer, appeared in the *Street Railway Journal* of March 4, 1905.

This company installed a " third " and " fourth " conductor rail on all of the above lines, both the conductor rails being of low carbon steel and supported on brown stoneware insulators. The insulators used in supporting the positive (outside) and negative (center) conductor rails are essentially of the same design on the individual roads, the top of the positive insulator being 1.5 in. higher than the negative. A malleable-iron cap and base is used on the District Railway insulators, the difference in height of the positive and negative insulator being partly in the depth of the insulation and partly in the design of the base.

No base or cap is used with any of the insulators on the Tube railways. The top of the positive conductor rail is 10 in. and 10.5 in. above the top of the sleepers on the District and tube railways respectively. Figs. 1 to 4 inclusive show the type of insulators, conductor rails, spacing, etc., as installed on the district and tube railways.

The direct-current track-circuit signal system has been installed on these roads and hence the desirability of not using the running rails as part of the main power circuit.

Leakage and Insulation Measurements

Metropolitan District Railway. An extended series of preliminary measurements and tests were made on the Hounslow and Putney section of the District Railway early in 1905 with a view of trying to account for the comparatively low insulation resistance of the negative conductor rail. These tests were made during the constructional period; that is, before the introduction of commercial electric trains but with the regular steam trains in daily commercial service, and the insulation of the conductor rails was therefore more or less of a variable quantity and subject to the temporary changes and conditions incidental to such work.

The positive (outside) conductor rail, particularly at the stations, was heavily coated with grease from the steam trains and this, together with loose ballast, dirt, etc., made it very difficult and virtually impossible to maintain good insulation during these tests.

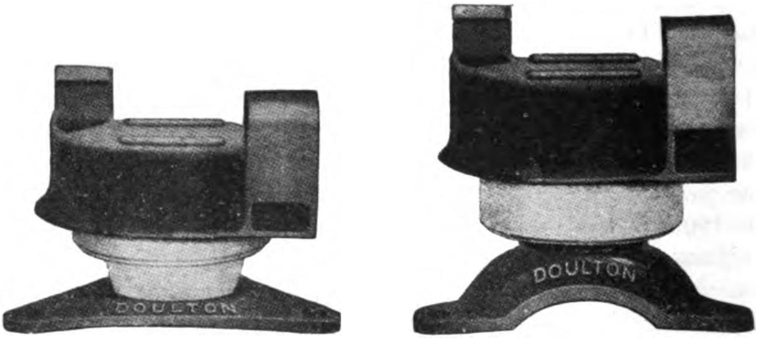


Fig. 1 Fig. 2

Positive and negative insulators—District Railway

The results of these preliminary measurements were very erratic, for the reasons just given, and are therefore not included in this paper. They plainly indicated, however, the existence of the peculiar phenomena observed on the tube railways where the conditions were much more favorable for the perfectly definite and consistent observations given herewith.

The observations given in Table 1 were made in January, 1906, and show the variation in potential between conductor rails and earth from day to day. These measurements were made on the main line of the District Railway at Earls Court, the electric trains having been in commercial service since July 1, 1905.

All sections of the road are tied together and cross-bonded through the sub-station bus-bars under normal operating conditions, and these results are therefore representative of the conditions existing over the entire District Railway system, collectively considered. The continuously bonded running rail was used as the earth connection for these measurements.

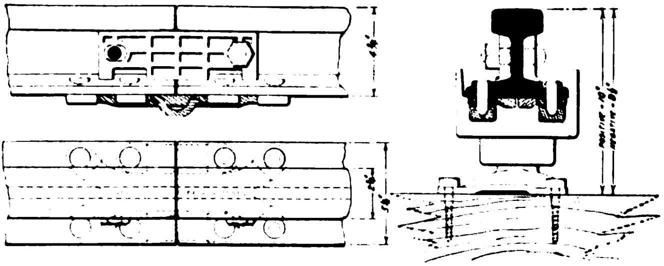
TABLE I.—LINE VOLTAGE 580

Date—1906	Time	Volts between earth and Positive	Volts between earth and Negative	Remarks
Jan. 8	2.15 p.m.	530	50	Ground very damp.
" 8	4.35 "	512	68	" " "
" 9	4.50 "	500	80	Ground very wet.
" 10	10.00 a.m.	529	51	Fine.
" 10	5.30 p.m.	512	68	Fine and dry.
" 12	11.00 a.m.	510	70	Fine, ground damp.
" 12	5.50 p.m.	512	68	" " "
" 13	11.00 a.m.	490	90	Ground very wet.
" 15	12.30 p.m.	540	40	Very fine.
" 15	6.00 "	520	60	Very fine and dry.
" 16	5.00 "	512	68	Showery.
" 18	12.45 "	478	102	Very wet.
" 22	5.00 "	520	60	Fine.
" 23	6.00 "	532	48	Fine, frosty.

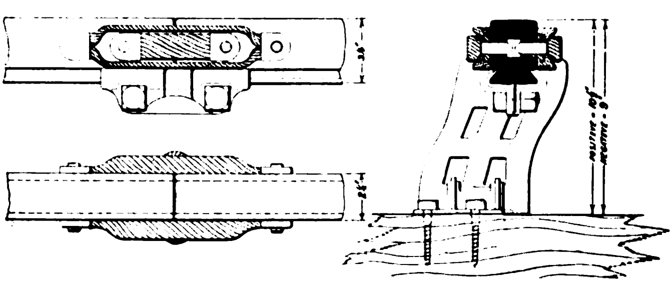
Baker Street and Waterloo Railway. The tests on this railway like those on the District Railway, were made about the end of the constructional period and were therefore subject, but in a much lesser degree, to the possibility of the same general disturbances.

The insulators were of brown stoneware with a good glaze, free from grease, and reasonably clean, with the exception of the usual dust from the small granite ballast and construction work. A rectangular section of conductor rail is used on this line, there being no intervening metal cap or support between the rails and insulators. These measurements were not subject to the usual outdoor variation of London weather and temperature, the section of track on which the measurements were made being entirely below the surface and far enough removed from the tunnel entrance so as to be, at the most, only possibly indirectly affected:

Up-road, January 2 to 4, 1906. The following measurements were made on the "up-road," between the cable passageway beneath the London Road sub-station and the far end of Baker street station platform, a distance of 18,317 ft. or 3.47 miles. All measurements were made from the London Road sub-station.



100 LB: RAIL — DISTRICT RAILWAY



85 LB: RAIL — TUBE RAILWAYS

Fig. 3—Bonding and supports for conductor rails

Polarity of conductor rails, normal.

Between positive (outer) and negative	570 volts
" " and earth	510 "
" negative and earth	60 "
Leakage, positive to negative	0.5 amperes
Leakage current per mile of single track	0.144 "
Leakage, positive earthed	5.0 "
" negative earthed	0.57 "

Current was on from 2 to 5.30 p.m. on January 1, and from 7 to 10 a.m. January 2; that is, 2.5 hours on the preceding

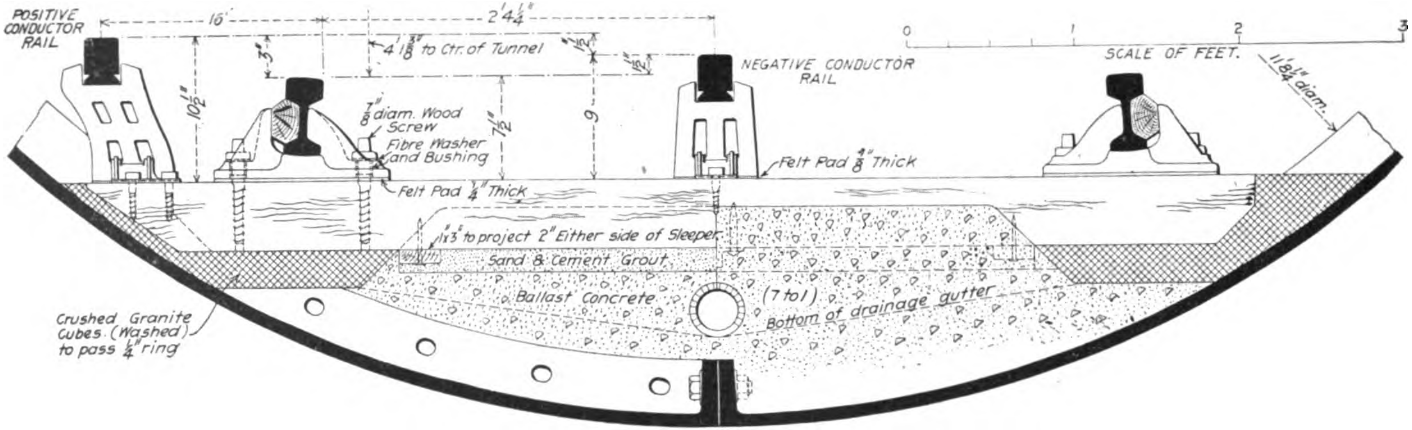


FIG. 4—Section illustrating type of construction, Tube Railways

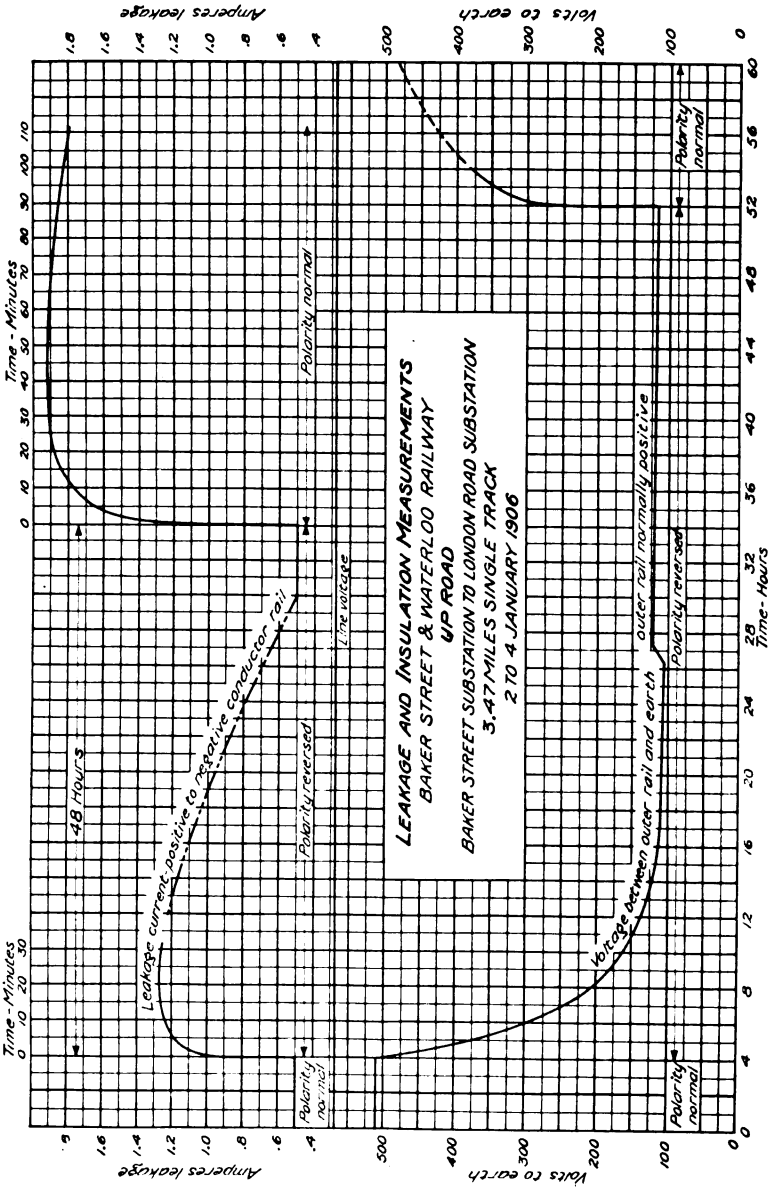

LEAKAGE AND INSULATION MEASUREMENTS
BAKER STREET & WATERLOO RAILWAY
UP ROAD
BAKER STREET SUBSTATION TO LONDON ROAD SUBSTATION
3.47 MILES SINGLE TRACK
2 TO 4 JANUARY 1906
Amperes leakage
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
Volts to earth
500
400
300
200
100
0
Time - Minutes
0
10
20
30
40
50
60
70
80
90
100
110
Time - Hours
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
48 Hours
Leakage current-positive to negative conductor rail
Voltage between outer rail and earth
outer rail normally positive
Line voltage
Polarity normal
Polarity reversed
Polarity normal
Polarity reversed
Polarity normal
Polarity normal

Fig. 5

afternoon and for 3 hours continuously and immediately preceding the above measurements. The insulators were supposed to have been cleaned prior to above measurements. Current had also been on these rails on several previous occasions for testing purposes and the running of trains.

Polarity of conductor rails, reversed. The polarity of the conductor rails was reversed immediately after the preceding readings and the pressure applied continuously for 48 hours, all other conditions remaining the same. Readings were taken regularly between the outer rail (now negative polarity) and earth, the results being shown on Fig. 5.

At the end of the 48 hours the following readings were taken:

Between positive (centre) and negative	570	volts
" " and earth	455	"
" negative and earth	115	"
Leakage, positive to negative	0.5	amperes
Leakage current per mile of single track	0.144	"
Leakage, positive earthed	2.8	"
" negative earthed	0.7	"

These results show that the potential between the outer rail and earth was reduced from 510 (positive to earth) to 104 volts (negative to earth) in 24 hours. Some local disturbance then caused a sudden rise to about 118 volts, after which it again slowly but steadily fell to 115 volts at the end of 48 hours. During the first half-hour immediately following the reversal, the leakage current increased steadily from 0.5 to 1.27 amperes and then gradually became less. It reached the normal value of 0.5 of an ampere on or *before* the end of the 48 hours. The low-reading ammeter was damaged by a temporary short-circuit about the end of the first hour and was therefore not immediately available for current measurements.

Polarity of conductor rails, normal. The polarity of the conductor rails was again made normal—immediately after the 48 hour run with the polarity reversed—the increase in leakage current and the variation in potential between the outer rail and earth for the first two hours being also shown in Fig. 5.

These latter measurements unfortunately could not be continued any longer as the road was needed for the running of trains.

The leakage current rose rapidly immediately following the change from reversed to normal polarity, the maximum value of 1.92 amperes being reached in about 35 minutes.

" *Up* " *road, January* 16, 1906. The conductor rails were alive an average of about nine hours per day, normal polarity, from January 4 to 16 inclusive for running trains a total of 117 hours between the readings on January 4 and the following readings on January 16, 1906.

Polarity of conductor rails, normal.

Between positive (outer) and negative	565 volts
" " and earth	530 "
" negative and earth	35 "
Leakage, positive and negative	0.32 amperes
Leakage current per mile single track	0.092 "
Leakage, positive earthed	5.70 "
" negative earthed	0.35 "

" *Up* " *road, January* 19 *to* 22, 1906. The following measurements show the effects of reversing the polarity of the conductor rails, the rails having been alive about 24 hours, normal polarity, for running trains between the tests of January 16 and 19. The rails were alive continuously for 43.5 hours between the readings of January 19 and 21 with the polarity reversed; that is, outer rail negative—and for 21 hours, normal polarity, between the readings of January 21 and 22. Fig. 6 gives full details of these tests and Fig. 5 the details of similar tests on the same road and under practically the same conditions. All the " Up " road measurements were made from the London Road sub-station.

General exhibit	Date of tests—1906		
	Jan. 19	Jan. 21	Jan. 22
Between positive and negative, volts	575	575	575
Between outer rail and earth, volts	531	112	530
Between centre rail and earth, volts	44	463	45
Leakage, positive to negative, amperes	0.29	0.35	0.3
Amperes leakage per mile single track	0.084	0.101	0.087
Leakage, outer rail earthed, amperes	4.3		
Leakage, centre rail earthed, amperes	0.3		
Approximate distance, miles	3.47	3.47	3.47

" *Down* " *road, January* 19 *to* 22 *and February* 12, 1906. The initial measurements for this road were made on January 19, 1906. The rails were alive continuously for about 8 hours previously to the initial measurements and for 17 hours, normal polarity, between the measurements on January 19 and 20. The normal polarity was reversed immediately after the read-

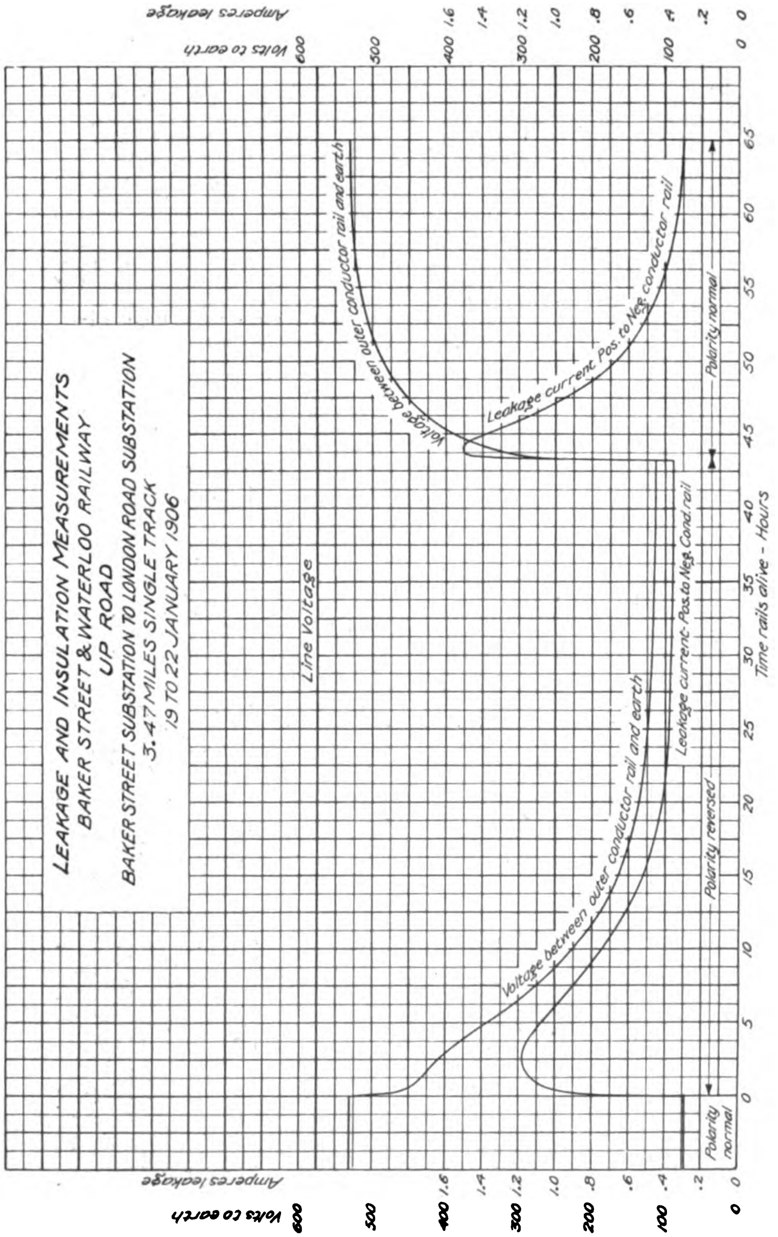

LEAKAGE AND INSULATION MEASUREMENTS
BAKER STREET & WATERLOO RAILWAY
UP ROAD
BAKER STREET SUBSTATION TO LONDON ROAD SUBSTATION
3.47 MILES SINGLE TRACK
19 TO 22 JANUARY 1906
Line Voltage
Voltage between outer conductor rail and earth
Voltage between outer conductor rail and earth
Leakage current Pos. to Neg. conductor rail
Leakage current-Pos. to Neg. Cond. rail
Polarity normal
Polarity reversed
Polarity normal
Amperes leakage
Volts to earth
600
500
400 1.6
1.4
300 1.2
1.0
200 .8
.6
100 .4
.2
0 0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Time rails alive - Hours

FIG. 6

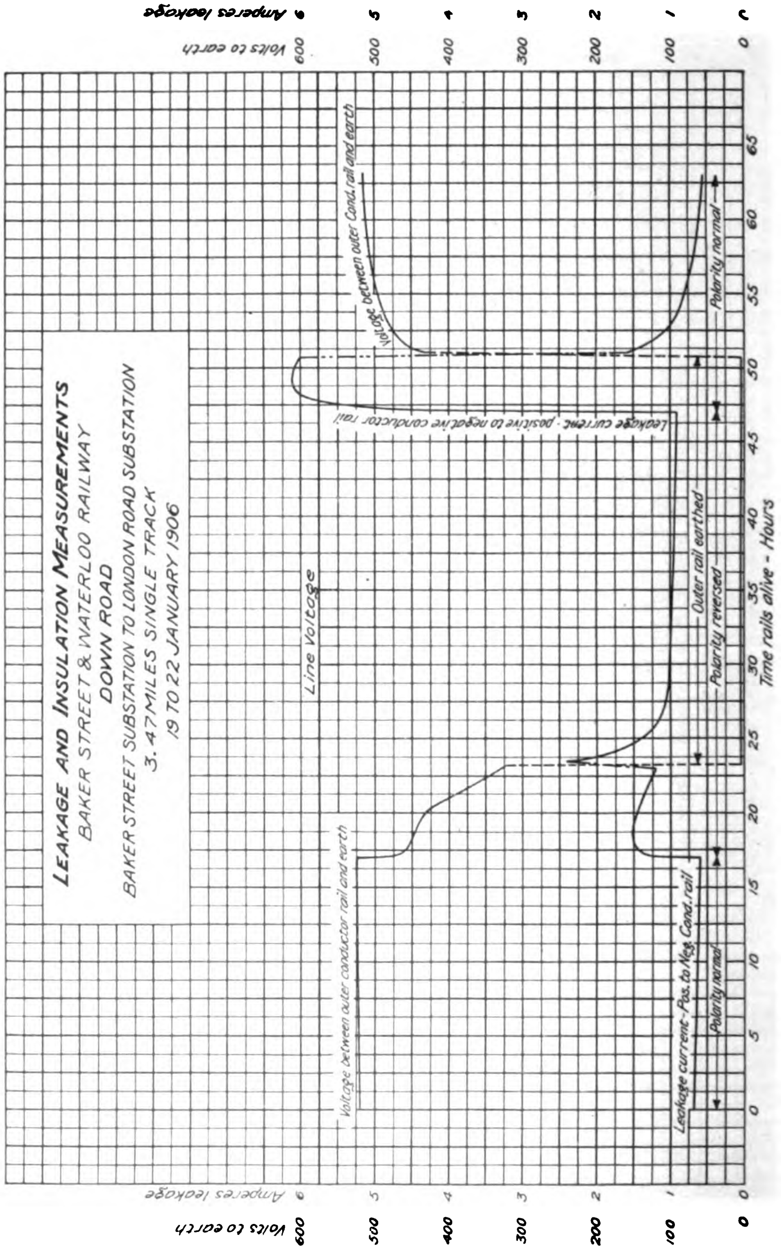

LEAKAGE AND INSULATION MEASUREMENTS
BAKER STREET & WATERLOO RAILWAY
DOWN ROAD
BAKER STREET SUBSTATION TO LONDON ROAD SUBSTATION
3.47 MILES SINGLE TRACK
19 TO 22 JANUARY 1906
Line Voltage
Voltage between outer conductor rail and earth
Voltage between outer Cond. rail and earth
Leakage current - positive to negative conductor rail
Leakage current - Pos. to Neg. Cond. rail
Polarity normal
Polarity reversed
Outer rail earthed
Polarity normal
Time rails alive - Hours
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Amperes leakage
0
1
2
3
4
5
6
Volts to earth
0
100
200
300
400
500
600

FIG. 7

ings on January 20 for 30 hours and again made normal for 15 hours, a total of 45 hours between the readings of January 20 and 22.

A temporary but effective " earth " mysteriously appeared on the outer rail about six hours after the reversal on January 20, this condition of affairs being maintained continuously for about 28 hours, four hours after the polarity was again made normal on January 21. The effect of this earth on the leakage current, together with the other details of this test, is shown in Fig. 7. The rails were alive daily, normal polarity, for the running of trains between the readings of January 22 and February 12, a total of about 260 hours between these readings. The readings for the " down " road, made at the Baker Street sub-station, are as follows:

General Exhibit	Date of tests—1906			
	Jan. 19	Jan. 20	Jan. 22	Feb. 12
Between positive and negative, volts..	575	575	575	575
Between outer rail and earth, volts...	520	525	515	499
Between centre rail and earth, volts...	55	50	60	76
Leakage, positive to negative, amperes	0.68	0.58	0.55	0.2
Amperes leakage per mile single track.	0.196	0.167	0.158	0.058
Leakage, outer rail earthed, amperes..	6.75			3.0
Leakage, centre rail earthed, amperes.	0.74	0.62		0.25
Approximate distance, miles..........	3.47	3.47	3.47	3.47

The following observations, Table 2, show the variations in potential between the positive conductor rail and earth—both roads--from day to day as well as the variation between the time of switching " on " and " off " on the same day. All measurements made by the sub-station attendants at the London Road sub-station, normal polarity.

DISCUSSION OF RESULTS

The following results are corroborated by many other measurements made during the years of 1903-1907, all of which plainly and unmistakably show the existence of the phenomena substantially as illustrated in Figs. 5, 6 and 7. There has been considerable study and investigation as to what actually takes place at the time of reversal, the general concensus of opinion being that it is an ordinary case of electrolytic action combined with ordinary insulation resistance conductivity. These results seem to depend upon one form of phenomenon which has long been known in connection with static charges; namely, that a negatively charged conductor leaks away its charge with much greater facility than does a positive; or virtually that under the same conditions a positively electrified conductor is better insulated. A negatively electrified conductor appears to be continuously discharging negative ions, which have the effect of conferring conductivity on the surrounding gas and of causing deposition of moisture from air more or less saturated. It is perfectly conceivable, therefore, that this negative discharge should favor the depositing of moisture between the surfaces of insulators progressively in such a manner that a slight conductivity might be conferred upon the insulator surfaces and that this effect

TABLE II.—LINE VOLTAGE 575

Date—1906	Time	Hours rails alive to-day	Volts between positive and earth	
			Up-road	Down-road
Jan. 24	7.00 p.m.	19	525	512
“ 25	10.30 a.m.		500	510
“ 25	8.00 p.m.	9.5	540	512
“ 26	10.00 a.m.		500	495
“ 26	7.30 p.m.	9.5	540	506
“ 27	10.00 a.m.		510	445
“ 27	3.30 p.m.	5.5	535	503
“ 29	10.00 a.m.		465	410
“ 29	7.00 p.m.	9.0	560	575
“ 30	10.00 a.m.		530	452
“ 30	8.30 p.m.	10.5	565	510
“ 31	8.00 a.m.		522	462
“ 31	8.30 p.m.	12.5	530	480
Feb. 1	9.00 a.m.		490	430
“ 1	7.30 p.m.	10.5	540	495
“ 2	8.30 a.m.		498	452
“ 2	7.30 p.m.	11.0	500	465
“ 3	8.00 a.m.		484	444
“ 3	4.30 p.m.	8.5		
“ 4	9.00 a.m.	15	463	440
“ 5	8.00 p.m.	20	493	469
“ 7	9.00 a.m.		505	480
“ 7	9.00 p.m.	12	505	495
“ 9	9.30 a.m.	14.5	486	444
“ 10	5.30 p.m.	17.5	520	492

might be expected to be absent with the positive side of the system. The film of liquid existing between the electrodes on a glass surface will gradually move from the positive to the negative electrode, and the negative insulators may therefore lose their insulating properties by having moisture drawn upon them, an action which does not take place on the positive side.

The reducing or chemical action of the ions liberated at the positive rail insulator may result in the formation of compounds which lower the resistance of the negative insulator, while the oxidation which takes place at the positive insulator may improve the insulation.

Conclusions. These results, whatever the immediate cause or the reason, have clearly demonstrated certain facts which are probably applicable to all similar installations and may be briefly summarized as follows:

1. That the difference of potential between the positive conductor and earth is always normally considerably greater than the potential existing between the negative conductor and earth.
2. That this difference between the positive and negative insulation becomes more marked the longer the conductors are subjected continuously to a difference of potential in the same direction.
3. That a reversal of the polarity is always instantly accompanied by a considerable increase in the normal leakage current between the positive and negative conductor.
4. The above phenomena can be repeated indefinitely and are independent of the length of time that the pressure has been previously applied to the conductors in either direction.
5. That the insulation of the negative conductor to earth can not be proportionately maintained.

Resistance of conductor rails. The resistance measurements given in Table 3 show about what may be expected commercially with a soft conductor rail containing an unusually small amount of manganese and carbon. The resistance of these rails was about 6.4 times that of an equivalent area of copper and the chemical composition substantially as follows:

Carbon	0.05
Manganese	0.19
Sulphur	0.06
Phosphorus	0.05
Silicon	0.03

It is interesting to note that the cost of this special conductor rail was no more than the standard track rail.

TABLE III.—RESISTANCE MEASUREMENTS

General exhibit	Section of railway			
	Hounslow	Putney	Wimbledon	B. St. & W.
General Data:				
Date of measurements	5/9/05	5/27/05	5/27/05	12/30/05
Net length measured, feet	88,300	37,700	53,500	36,600
Weight of rail per yd., lb.	100	100	100	85
Area of rail, sq. in.	9.86	9.86	9.86	8.3
Temp. of rails, deg. cent.	25	25	25	11.5
No. of switchboard contacts	0	4	4	2
No. of terminal post contacts	20	20	32	6
No. of rail contacts	20	24	44	36
No. of bonds per joint	4	4	4	4
Total no. of bonded joints.	2,107	834	1,160	1,095
Area bonds per joint, sq. in.	1.57	1.57	1.57	1.33
Contact area per joint, sq. in	9.4	9.4	9.4	12.56
Measurements.				
A, Total resistance	0.55309	0.24405	0.36412	0.24088
B, Total resistance	0.54856	0.22992	0.35013	0.23353
A, Res. per 1000 rail-ohm	0.006264	0.006473	0.006806	0.006581
B, Res. per 1000 rail-ohm	0.006213	0.006099	0.006544	0.006381
A. Res. per mile-ohm	0.033070	0.034180	0.035936	0.03475
B, Res. per mile-ohm	0.032805	0.032203	0.034552	0.03369
A, Equiv. cu. area, sq. in.	1.328	1.285	1.222	1.2
B, Equiv. cu. area, sq. in.	1.339	1.364	1.271	1.236
A, Rel. resistance, cu. at 1.	7.42	7.67	8.07	6.92
B, Rel. resistance, cu. at 1.	7.36	7.22	7.75	6.72
B, Contact res. per jt., ohm.	0.0000341	0.0000316	0.0000528	0.00001044
B, Contact res. per bond terminal, ohm	0.0000681	0.0000632	0.0001056	0.00002088

A includes the resistance of all feeder, track and jumper cables and the terminal post, rail and switchboard contact resistance; that is, the resistance of the bonded conductor rails, cables and contacts as installed and ready for commercial service.

B same as "A" less the calculated resistance of all feeder, track and jumper cables; that is, includes the resistance of the bonded conductor rails and auxiliary contacts.

Remarks. All calculated resistances are based on the temperature at which the measurements were made.

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(*Subject to final revision for the Transactions.*)

THREE-PHASE POWER-FACTOR

BY AUSTIN BURT

Based on the commonly accepted definition of power-factor, as " The ratio of true power to volt-amperes ", there can be no single factor that will exactly express such a physical relationship in a delta-connected, unsymmetrical, three-phase system.

It is possible, however, to determine, by practical methods, the weighted mean of the three power-factors of the single-phase paths of such a three-phase system, and to express that value by a single-factor. It has been suggested that such a factor might have importance under certain commercial conditions.

It is the purpose of this paper, first, to derive from the various relations that exist between the electromotive forces and currents in a three-phase, delta-connected system, a general expression which will enable the mean power-factor to be determined exactly; and, secondly, to develop a method by which the required values employed in the above expression may be readily determined from the standard switchboard instruments.

It is proposed, therefore, to find an expression for the total energy volt-amperes and for the total volt-amperes in the general case of a three-phase system in which the electromotive forces and currents in the single-phase paths may have any assigned value and phase relation. The ratio of these two expressions will be the desired mean power-factor. The total volt-amperes will be taken as derived from the total wattless volt-amperes and the total energy volt-amperes, or, in other words, from the sum of the wattless volt-amperes and from the sum of the energy volt-amperes existing in each single-phase path.

In the simple case of a single-phase system let

E = the impressed electromotive force
I = the current in the circuit resulting from inductive conditions in the receiver
ϕ = time-angle between E and I.

Fig. 1 will represent vectorially such a single-phase system. Then if the energy volt-amperes be represented by P, and wattless volt-amperes by P_w, we have,

$$P = I \cos\phi\, E \qquad (1)$$

$$P_w = I \sin\phi\, E \qquad (2)$$

From the definition of power-factor we have,

$$\text{power-factor} = \frac{P}{I\,E} = \frac{I \cos\phi\, E}{I\,E} = \cos\phi \qquad (3)$$

and,

$$\phi = \cos^{-1}\ (\text{power-factor}) \qquad (4)$$

from (1) and (2),

$$I\,E = \frac{P}{\cos\ \phi} = \frac{P_w}{\sin\ \phi} \qquad (5)$$

and by multiplication,

$$\frac{\sin\ \phi}{\cos\ \phi} = \frac{P_w}{P} = \tan\phi \qquad (6)$$

then from (6) and (4),

$$\phi = \tan^{-1}\left(\frac{P_w}{P}\right) = \cos^{-\prime}\ (\text{power-factor}) \qquad (7)$$

It is seen, therefore, that the angle ϕ, whose tangent is the ratio of the wattless ampere-volts to the energy ampere-volts, will give directly the power-factor from its cosine. A general expression for the total wattless ampere-volts and the total energy ampere-volts in a three-phase system, gives a ratio whose value is a weighted mean of the similar ratios of the several single-phase paths, and the angle whose tangent is this mean ratio gives the mean power-factor desired from its cosine.

In the three-phase system under consideration the total wattless ampere-volts is the algebraic sum of the wattless ampere-volts, and the total energy ampere-volts is the sum of the energy ampere-volts in each of the three single-phase paths of the system.

Such a three-phase system is represented by the vector diagram in Fig. 2. Let the impressed electromotive forces and currents in the single-phase windings be represented respectively by E_{ab}, E_{bc}. E_{ca}, and i_a, i_b, i_c, and the phase relations between the several electromotive forces and currents by α', β', γ', with the additional convention that angles measured counter clockwise are lagging, and measured clockwise they are leading.

In Fig. 2, then, the delta $(a\ b\ c)$ represents the value and phase relation between any selected values of E_{ab}, E_{bc}, and E_{ca}. The current in phase $a\ b$ and its phase relation to E_{ab} is represented by vector i_a at angle α' with E_{ab}. Similarly the currents in phases $b\ c$ and $c\ a$ are represented by vectors i_b at b and i_c at c, making lag-angles β' and γ' respectively with E_{bc} and E_{ca}. It should be remarked that angles α', β' and γ' could just as well have been taken leading as lagging.

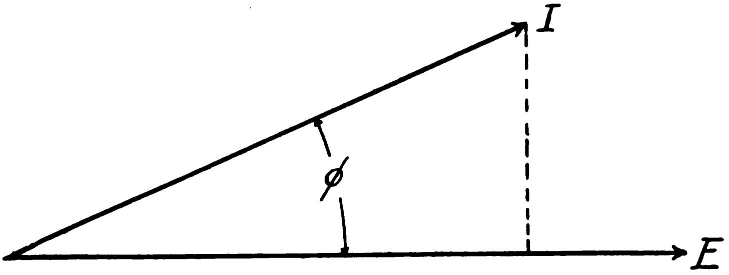

FIG. 1

The star or line current will be the resultant of the currents in any two adjacent paths; that is, the current at a will be the resultant of the single-phase current in $c\ a$, or i_c, and the current in $a\ b$, or $-i_a$.

i_c is represented at a by the broken vector $a\ a''$, and $-i_a$ by vector $a\ a'$. The resultant of these two vectors, I_a, therefore represents, in length and position, the line current at a. Similarly, the line current at b is the resultant of i_a and $-i_b$, which are represented at b by $b\ b''$ and $b\ b'$ respectively. Therefore, vector I_b represents, in length and position, the line current at *b*. And again, at *c*, the vector I_c is the resultant of i_b and $-i_c$, represented by the vectors $c\,c''$ and $c\,c'$, and it therefore represents the line current at *C*.

This diagram therefore illustrates graphically the essential

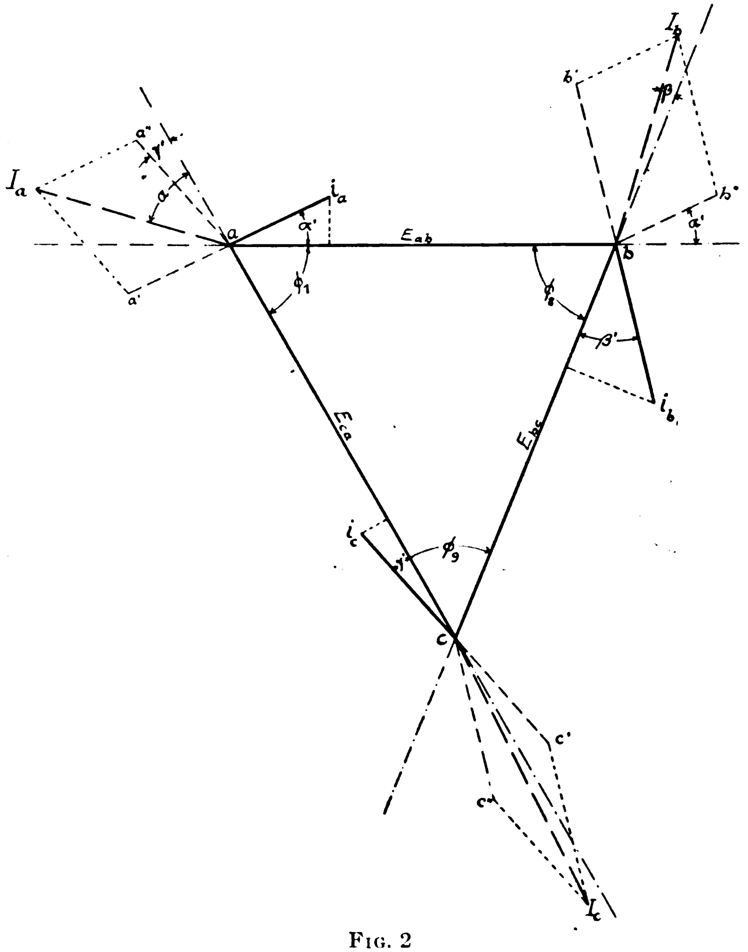

Fig. 2

elements, in general, of any delta-connected, three-phase system.

The energy ampere-volts in phase *a b*, in phase *b c*, and in phase *c a* are then, if P_{ab}, P_{bc}, and P_{ca} represent the respective single-phase paths,

$$P_{ab} = i_a \cos \alpha, E_{ab} \qquad (8)$$

$$P_{bc} = i_b \cos \beta' E_{bc} \qquad (9)$$

$$P_{ca} = i_c \cos \gamma' E_{ca} \qquad (10)$$

adding (8), (9) and (10) for total energy ampere-volts,

$$P = i_a \cos \alpha' E_{ab} + i_b \cos \beta' E_{bc} + i_c \cos \gamma' E_{ca} \qquad (11)$$

Similarly the wattless ampere-volts, if $(P_w)_{ab}$, $(P_w)_{bc}$ and $(P_w)_{ca}$ represent the respective single-phase paths, are,

$$(P_w)_{ab} = i_a \sin \alpha' E_{ab} \qquad (12)$$

$$(P_w)_{bc} = i_b \sin \beta' E_{bc} \qquad (13)$$

$$(P_w)_{ca} = i_c \sin \gamma' E_{ca} \qquad (14)$$

adding (12), (13) and (14) for total wattless ampere-volts,

$$P_w = i_a \sin \alpha' E_{ab} + i_b \sin \beta' E_{bc} + i_c \sin \gamma' E_{ca} \qquad (15)$$

Since it is ordinarily inconvenient, if not impossible, to make measurements in the single-phase paths of a three-phase system it is required to find more useful expressions than (11) and (15). General expressions, based on and equal to (11) and (15), with external values for electromotive forces and currents, may be derived by a consideration of the relations existing in vector diagram, Fig. 3. This diagram is in all essential particulars an exact duplicate of Fig. 2. It is desired to prove from it that the following general proposition is true: that for any selected position of point O whatsoever, with lines $O\,e$, $O\,f$ and $O\,g$ passing through the delta vertices a, b, and c, respectively, the sum of the products of the projection $a\,e$, of line-current vector I_a on $O\,e$, by $O\,a$, and the projection $b\,f$, of line current I_b on $O\,f$, by $O\,b$, and the projection $c\,g$, of line-current vector I_c on $O\,g$, by $O\,c$ is equal to P the total energy volt-amperes and therefore equal to and may be substituted for equation (11).

Similarly, it is desired to prove that the sum of the products of $e\,a''$ by $O\,a$, and $f\,b''$ by $O\,b$ and $g\,c''$ by $O\,c$ is equal to P_w the total wattless volt-amperes, and therefore equal to and may be substituted for equation (15).

Expressing these statements in form it is desired to prove that,

$$P \ = I_a \cos \alpha'' O\, a + I_b \cos \beta'' O\, b + I_c \cos \gamma'' O\, c \qquad (16)$$

$$P_w = I_a \sin \alpha'' O\, a + I_b \sin \beta'' O\, b + I_c \sin \gamma'' O\, c \qquad (17)$$

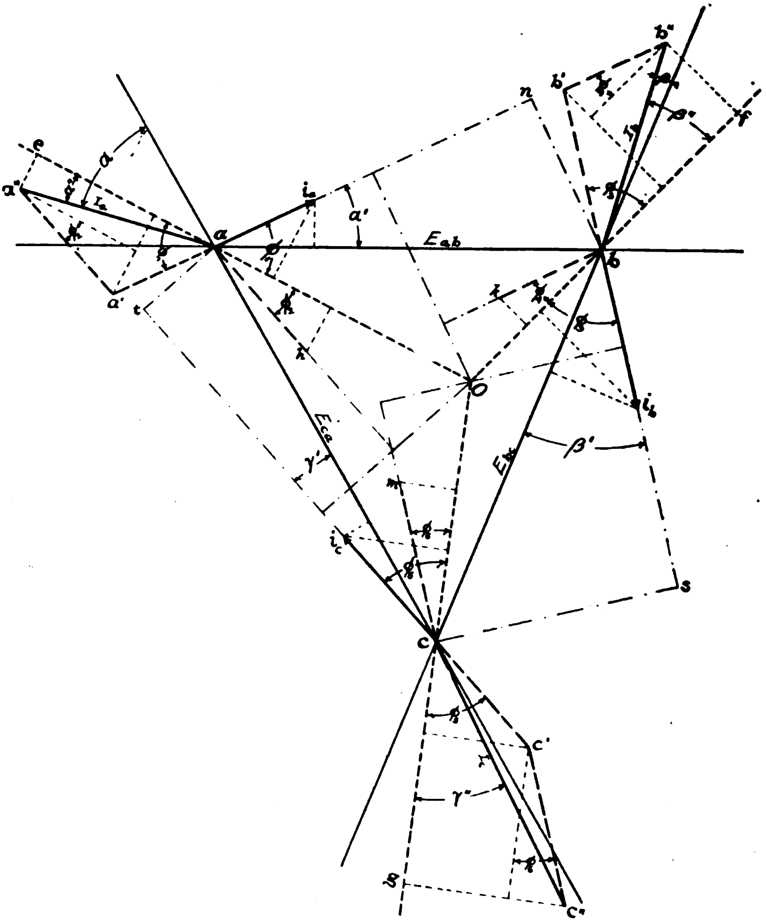

FIG. 3

Referring, successively, to the following pairs of triangles, $a\,O\,b$ and $a\,n\,b$, $b\,O\,c$ and $b\,s\,c$, $c\,O\,a$ and $c\,t\,a$, and noting that $b\,k$ is equal to and parallel with vector i_a, that $c\,m$ is equal to and parallel with vector i_b, and, finally, that $a\,h$ is equal to and parallel with vector i_c, we have the following set of equations:

$$i_a E_{ab} \cos \alpha' = i_a O a \cos \phi_1 + i_a O b \cos \phi_4 \qquad (18)$$

$$i_b E_{bc} \cos \beta' = i_b O b \cos \phi_3 + i_b O c \cos \phi_6 \qquad (19)$$

$$i_c E_{ca} \cos \gamma' = i_c O c \cos \phi_5 + i_c O a \cos \phi_2 \qquad (20)$$

$$i_a E_{ab} \sin \alpha' = i_a O a \sin \phi_1 - i_a O b \sin \phi_4 \qquad (21)$$

$$i_b E_{bc} \sin \beta' = i_b O b \sin \phi_3 + i_b O c \sin \phi_6 \qquad (22)$$

$$i_c E_{ca} \sin \gamma' = i_c O c \sin \phi_5 - i_c O a \sin \phi_2 \qquad (23)$$

adding (18), (19), and (20) and referring to (11), we have,

$$\begin{aligned} &i_a \cos \alpha' E_{ab} + i_b \cos \beta' E_{bc} + i_c \cos \gamma' E_{ca} = P = \\ &\quad (i_a \cos \phi_1 + i_c \cos \phi_2) O a + (i_b \cos \phi_3 + i_a \cos \phi_4) O b + \\ &\quad (i_c \cos \phi_5 + i_b \cos \phi_6) O c \qquad (24) \end{aligned}$$

but from Fig. 3, by inspection,

$$\begin{aligned} &(i_a \cos \phi_1 + i_c \cos \phi_2) O a = (a a' \cos \phi_1 + a' a'' \cos \phi_2) O a = a e. \\ &\quad O a = I_a \cos \alpha'' O a \qquad (25) \end{aligned}$$

and

$$\begin{aligned} &(i_b \cos \phi_3 + i_a \cos \phi_4) O b = (b b' \cos \phi_3 + b' b'' \cos \phi_4) O b = b f. \\ &\quad O b = I_b \cos \beta'' O b \qquad (26) \end{aligned}$$

and

$$\begin{aligned} &(i_c \cos \phi_5 + i_b \cos \phi_6) O c = (c c' \cos \phi_5 + c' c'' \cos \phi_6) O c = c g. \\ &\quad O c = I_c \cos \gamma'' O c \qquad (27) \end{aligned}$$

substituting these results in (24) we have,

$$P = I_a \cos \alpha'' O a + I_b \cos \beta'' O b + I_c \cos \gamma'' O c \qquad (28)$$

thus proving equation (16).

Similarly adding (21), (22), and (23), there are, referring also to (15),

$$i_a \sin\alpha'\, E_{ab} + i_b \sin\beta'\, E_{bc} + i_c \sin\gamma'\, E_{ca} = P_w =$$
$$(i_a \sin\phi_1 - i_c \sin\phi_2)\, O\,a + (i_b \sin\phi_3 - i_a \sin\phi_4)\, O\,b +$$
$$(i_c \sin\phi_5 + i_b \sin\phi_6)\, O\,c \qquad (29)$$

but from Fig. 3 by inspection,

$$(i_a \sin\phi_1 - i_c \sin\phi_2)\, O\,a = (a\,a' \sin\phi_1 - a'\,a'' \sin\phi_2)\, O\,a = e\,a''.$$
$$O\,a = I_a \sin\alpha''\, O\,a \qquad (30)$$

and

$$(i_b \sin\phi_3 - i_a \sin\phi_4)\, O\,b = (b\,b' \sin\phi_3 - b'\,b'' \sin\phi_4)\, O\,b = f\,b''.$$
$$O\,b = I_b \sin\beta''\, O\,b \qquad (31)$$

and

$$(i_c \sin\phi_5 + i_b \sin\phi_6)\, O\,c = (c\,c' \sin\phi_5 + c'\,c'' \sin\phi_6)\, O\,c = g\,c''.$$
$$O\,c = I_c \sin\gamma''\, O\,c \qquad (32)$$

substituting these results in (29) we have,

$$P_w = I_a \sin\alpha''\, O\,a + I_b \sin\beta''\, O\,b + I_c \sin\gamma''\, O\,c \qquad (33)$$

thus proving equation (17).

Equations (28) and (33) are general expressions for any possible location of point O. If, therefore, point O be taken at vertex c in Fig. 3 there are:

$$\begin{array}{ll} \alpha'' = \alpha & O\,a = E_{ca} \\ \beta'' = \beta & O\,b = E_{bc} \\ & O\,c = 0 \end{array}$$

substituting these values in (28) and (33) there are:

$$P = I_a \cos\alpha\, E_{ca} + I_b \cos\beta\, E_{bc} \qquad (34)$$

$$P_w = I_a \sin\alpha\, E_{ca} + I_b \sin\beta\, E_{bc} \qquad (35)$$

Let

$$P_{ca} = I_a \cos\alpha\, E_{ca} \qquad (36)$$

$$P_{bc} = I_b \cos\beta\, E_{bc} \qquad (37)$$

then from (34),

$$P = P_{ca} + P_{bc} \qquad (38)$$

A standard three-phase wattmeter, consisting essentially of two single-phase measuring elements, if placed in the system represented by Fig. 2, with the current coil of one element in line current represented by vector I_a and electromotive force coil across phase $c\,a$, and with the current coil of the second element in line current represented by vector I_b and electromotive force coil across phase $b\,c$, will measure by the first element that portion of total power, P, expressed by P_{ca}, and by the second element that portion expressed by P_{bc}, the two combined giving the total energy ampere-volts, P.

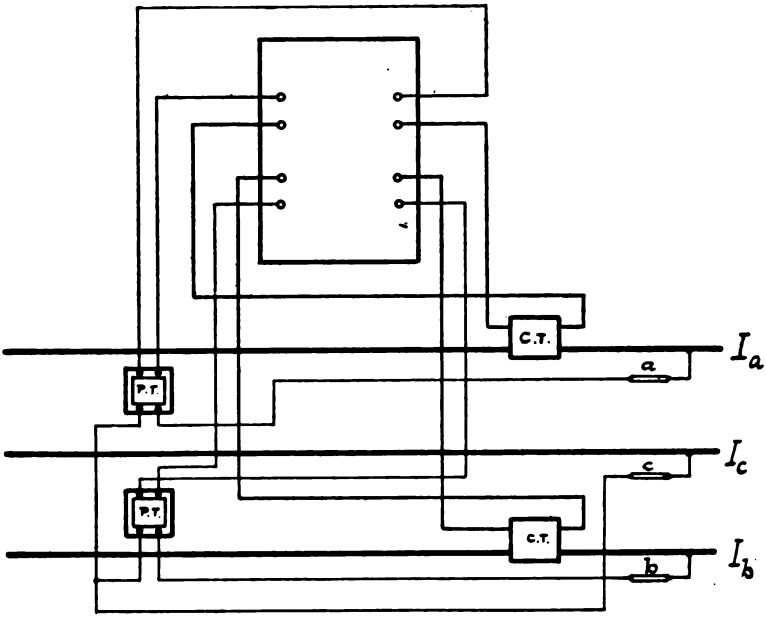

FIG. 4

It will be observed by a comparison of (34) and (35), that P_w may be derived from P by substituting the sines of α and β for the cosines, and further it will be observed, that α and β may be obtained from (36) and (37) provided the single-phase elements of the three-phase wattmeter could be read separately.

A method for accomplishing this result consists in causing to become inoperative, first one element and then the other, by opening the potential circuit of the element. Fig. 4 shows a standard connection of a three-phase switchboard wattmeter operated by current and potential transformers. At a, b and c

are shown the usual primary fuses for the potential transformer. I_a, I_b and I_c are the line currents. By removing fuse *b* the wattmeter element operated by current I_b and electromotive force across *b c* becomes inoperative and a reading taken from the instrument is expressed by (36) or,

$$P_{ca} = I_a \cos \alpha \, E_{ca}$$

from which,

$$\operatorname{Cos} \alpha = \frac{P_{ca}}{I_a \, E_{ca}} \tag{39}$$

Similarly by the removal of fuse *a*, Fig. 4, the other element becomes inoperative, and by replacing the first fuse, a second reading from the instrument is expressed by (37), or

$$P_{bc} = I_b \cos \beta \, E_{bc}$$

from which,

$$\operatorname{Cos} \beta = \frac{P_{bc}}{I_b \, E_{bc}} \tag{40}$$

As line currents, I_a and I_b, and voltages, E_{ca} and E_{bc}, are readily found from standard switchboard ammeters and voltmeters, (39) and (40) can be easily solved for α and β, the sines of which substituted in (35) will give the total wattless volt-amperes, P_w.

Having demonstrated that equations (34) and (35) are true and derived from general expressions for P and P_w, and that they may be solved practically, it follows that values determined by them when substituted in equation (7) will give the desired value for ϕ and thus also the proposed mean power-factor.

It may be of interest to take the simple case of a single-phase load in the three-phase system under consideration, and derive the power-factor by this method.

The same values may be assumed as represented by Fig. 2, with the single-phase inductive load in phase *a b*, and represented by i_a. Currents i_b and i_c will be absent from phases *b c* and *c a*, and therefore equal to zero.

This condition of affairs is represented more plainly by Fig. 5, in which,

$$\begin{array}{lll} I_a = i_a & \phi_1 = \alpha = \alpha' + \phi_7 & O\,a = E_{ca} \\ I_b = i_a & \phi_4 = \beta = \phi_8 - \alpha' & O\,b = E_{bc} \\ I_c = 0 & & O\,c = 0 \end{array}$$

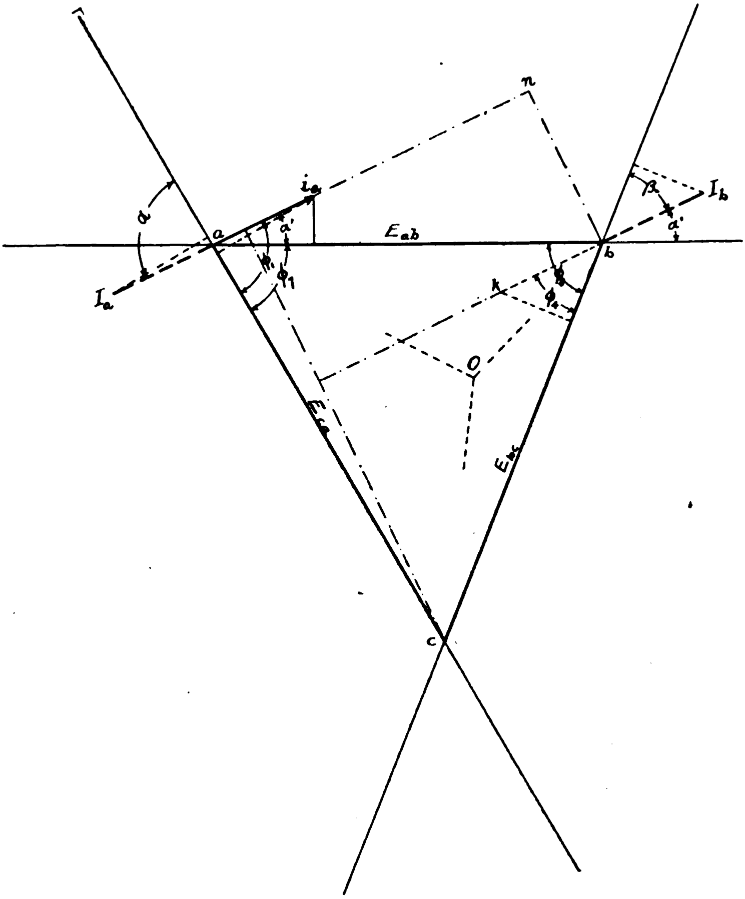

FIG. 5

substituting these values in equation (24), and (29)

$$P = I_a \cos(\alpha' + \phi_7)\, E_{ca} + I_b \cos(\phi_8 - \alpha')\, E_{bc} \tag{41}$$

$$P_w = I_a \sin(\alpha' + \phi_7)\, E_{ca} - I_b \sin(\phi_8 - \alpha')\, E_{bc} \tag{42}$$

But it is seen from Fig. 5 that,

$$E_{ca} \cos (\alpha'+\phi_7) + E_{bc} \cos (\phi_8 - \alpha') = E_{ab} \cos \alpha' \tag{43}$$

$$E_{ca} \sin (\alpha'+\phi_7) - E_{bc} \sin (\phi_8 - \alpha') = E_{ab} \sin \alpha' \tag{44}$$

substituting in (41) and (42) and dividing (42) by (41), remembering that $I_a = I_b = i_a$, we have,

$$\text{Tan } \phi = \frac{P_w}{P} = \frac{E_{ab} \sin \alpha' i_a}{E_{ab} \cos \alpha' i_a} = \tan \alpha' \tag{45}$$

Therefore $\phi = \alpha'$ and since their cosines are necessarily equal, the mean power-factor must equal the power-factor of the single-phase winding *a b*.

As this is a general solution of the single-phase case, it follows that it will be true for any assigned conditions as to electromotive force, current, or phase-relation.

Assuming the above single-phase load to be non-inductive, α' will then be zero and from (45),

$$\text{Tan } \phi = \frac{P_w}{P} = \frac{E_{ab} \sin 0\, i_a}{E_{ab} \cos 0\, i_a} = \frac{0}{1} = 0$$

$0 = \cos^{-1} (1)$, therefore power-factor equals unity.

Still another simple case is that of the balanced three-phase load, equal electromotive forces and uniform phase-relations in the single-phase windings. For convenience, this phase relation will be taken as 30° lagging.

Referring to Fig. 2 there will be,

$$\begin{aligned} E_{ab} &= E_{bc} = E_{ca} = E \\ i_a &= i_b = i_c = i \\ \alpha' &= \beta' = \gamma' = 30^\circ \\ I_a &= I_b = I_c = I \end{aligned}$$

By inspection from Fig. 2,

$$\phi_7 = \phi_8 = \phi_9 = 60^\circ$$

and

$$\begin{aligned} \text{angle } a'\, a\, a'' &= \phi_7 + \alpha' - \gamma' \\ &= 60^\circ + 30^\circ - 30^\circ = 60^\circ \end{aligned}$$

therefore, since $a\,a' = a\,a'' = i$, there is

$$\alpha = \tfrac{1}{2} \text{ angle } a'\,a\,a'' + \gamma' = 30^\circ + 30^\circ = 60^\circ$$

and also,

$$\begin{aligned} \text{angle } b'\,b\,b'' &= \phi_8 + \beta' - \alpha' \\ &= 60^\circ + 30^\circ - 30^\circ = 60^\circ \end{aligned}$$

therefore, since $b\,b' = b\,b'' = i$, there is

$$\beta = \tfrac{1}{2} \text{ angle } b'\,b\,b'' + \alpha' - \phi_8 = 30^\circ + 30^\circ - 60^\circ = 0^\circ$$

substituting these values in (34) and (35),

$$\begin{aligned} P &= I\,E \cos 60^\circ + I\,E \cos 0^\circ \\ &= I\,E\,(\tfrac{1}{2} + 1) = 3/2\,I\,E \\ P_w &= I\,E \sin 60^\circ + I\,E \sin 0^\circ \\ &= I\,E\,(\tfrac{1}{2}\sqrt{3} + 0) \end{aligned}$$

substituting in (7),

$$\phi = \tan^{-1}\left(\frac{\tfrac{1}{2}\sqrt{3}\,I\,E}{\tfrac{3}{2}\,I\,E}\right) = \tan^{-1}\left(\frac{1}{\sqrt{3}}\right) = 30^\circ$$

Therefore,

$$\text{power-factor} = \cos 30^\circ$$

In conclusion, the following practical illustration will emphasize the proposed method. It may be remarked in passing that the values taken are those used in Fig. 2.

Using the same nomenclature as in the previous demonstration there are,--

E_{ab} = 2.050 kilovolts. I_a = 214.8 amperes.
E_{bc} = 2.248 " I_b = 228.5 "
E_{ca} = 2.400 " I_c = 312.2 "
P_{ca} = 371.49 kilowatts, P_{bc} = 511.30 kilowatts

from (38),

$$P = 371.49 + 511.30 = 882.79 \text{ kilowatts.}$$

from (39) and (40),

$$\text{Cos } \alpha = \frac{371.49}{214.8 \times 2.400} = \cos\,(43^\circ\ 54')$$

$$\text{Cos}\ \beta = \frac{511.30}{228.5\times 2.248} = \cos\ (5^\circ\ 36')$$

whence,

$$\text{Sin}\ \alpha = \sin\ (43^\circ\ 54') = 0.6935$$
$$\text{Sin}\ \beta = \sin\ (5^\circ\ 36') = 0.0977$$

substituting in (35),

$P_w = 214.8 \times 0.6935 \times 2.400 + 228.5 \times 0.0977 \times 2.248 = 357.46 + 50.18 = 407.64$ wattless kilovolt-amperes.

Substituting these values of P and P_w in (7),

$$\phi = \tan^{-1}\left(\frac{407.64}{882.79}\right) = 24^\circ\ 47'$$

therefore,

$$\text{power-factor} = \cos\ (24^\circ\ 47') = 0.908.$$

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FROM STEAM TO ELECTRICITY ON A SINGLE TRACK ROAD

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As bearing on the general problem of conversion from steam to electricity for railroad operation, attention may be drawn to the probable influence of the methods followed and results obtained in equipping single-track roads. Of the total mileage in this country, about 60% is single track. The conditions obtaining on such roads are necessarily widely different from those on the large trunk-line sections which have been recently electrically equipped. While the several notable papers which have recently appeared on this and kindred subjects have taken quick advantage of the data available from the short periods of operation of several large installations, it cannot be said that the conditions in those cases are typical of more than a part of the entire problem.

Between the interurban road of comparatively light units and the large trunk-line installation with locomotive equipment, there is an intermediate class of steam road which, if equipped with electricity, should furnish excellent indication as to the results to be expected in the larger projects. These roads have usually single track and operate combined passenger and freight traffic over moderate distances. Unfortunately, the change in this type of road cannot often be made attractive on the ground of increased economy of operation; the transfer is usually accompanied by such an increase in fixed charges as to more than offset the economies possible under electrical operation. The road described in this paper is no exception in this respect, but, as is often the case, other considerations were deemed important enough to justify the change to electricity. The road has a long steam history which should permit excellent opportunities for comparison of results under steam and electricity. The considerations leading to the adoption of the 6600-volt, single-phase, alternating-current system are given at some length; opportunity is taken to review the authority for several engineering constants commonly accepted; and an estimate is made as to the probable effect of the change on the cost of operation.

The road. The Annapolis Short Line, a property of the Maryland Electric Railways Company, is a single-track, standard gauge steam road between Baltimore and Annapolis. Its length is 25.25 miles and in addition there is a branch 4 miles long extending south of Annapolis to Bay Ridge, a summer resort on Chesapeake Bay. The Baltimore terminal is Camden Station, the main terminal of the Baltimore & Ohio Railroad. At Annapolis the entrance is direct into the Short Line's own terminal, at which point are located its shops, roundhouse, car barns, etc. The maximum gradient is 1.5%, the longest stretch at this figure being 1.5 miles. There is one curve of 8°, one of 6°, several of 4° 30′, and many of easier figure. There are three bridges, one of them, over the Severn River being 3700 ft. long and two have draws. The rail is 80 lb.; the ballast gravel and cinder. The present normal service comprises seven trains per day, averaging three coaches each, in each direction. The approximate monthly car-mileage is 30,000. The fastest time is 45 minutes between terminals with 5 intermediate stops, a schedule speed of 33.7 miles per hour. There is one train per day of this class in each direction. The local running time is 1 hour with an average of 15 stops, a schedule speed of 25.25 miles per hour. There is one freight train each way daily and there are occasional large excursion loads.

Aside from the demands of a constant high-class patronage between the two cities, the conditions imposed by operation over more than a mile of the crowded B. & O. R.R. tracks and into its terminal, have resulted in excellent operating efficiency and schedule maintenance.

Reasons for change to electricity. The objects sought in changing to electrical operation were increased car-mileage, more frequent service, express service at least as fast, cleaner service, and the sentimental and indefinable attraction inherent in electrical operation. It is evident that the first three of these objects could be attained with much less initial expenditure by increasing the rolling stock, double tracking, installing block signals, etc. Difficulty might be met in the Baltimore terminal of the B. & O. R.R., where the number of train movements in and out attendant upon turning a locomotive and the time consumed, are already limiting factors. It would appear, however, that this difficulty also might be met by the use of double-end locomotives.

Elsewhere in this paper a comparison is made of operating expenses, maintenance, and interest charges for steam and electric operation of the present schedule. The comparison indicates that the operating and maintenance expenses alone would be about the same in the two cases; with interest charges included, however, the total of these items combined would be increased about 16% in changing from steam to electricity. While a part of this increase is due to the high price paid for power, it will be evident, notwithstanding, that the conditions are not such as to offer any prospect of increased economy of operation by electricity. Reasons are present, however, which in the eyes of the controlling interests are sufficiently cogent to more than overcome this objection, and to justify the abandonment of steam.

Owing to the fixed nature of the traffic to and from Annapolis, and to the fact that the local business is only 25% of the total, the direction in which increased business may be looked for is in the development of the region between the two cities. As the road runs for about 8 miles along the north side of Round Bay and Severn River, through high and attractive country, the prospect is unusually good and already attested by the rise in real estate values. It is believed that this development, slow in the past under steam, will be an early result of frequent electric service. Further, the aim is to develop excursion business to Bay Ridge to a degree not possible with steam. The superiority of electricity for this class of service is well known. Finally the Washington, Baltimore & Annapolis Railroad, to a certain extent a parallel line, and formerly a steam road, is also changing to electricity and is extending its tracks to city streets at each end. The distance from Annapolis to Baltimore by this route is about 15% greater than by the Short Line, and the latter has at present about 80% of the through business. The two roads are not competitive in local business, as they lie on opposite sides of the Severn River. The practical necessity for electrification on the part of the Short Line is evident. This, therefore, is one further instance in which the adoption of electricity is caused not by any prospect of better economy of operation, and not because it was more attractive in first cost than steam for increasing service. The reasons are found in special local conditions, and in the confidence that electric service will increase business to a degree not possible with steam.

Power supply. There are in Baltimore two 25-cycle, 13,200-volt, three-phase power plants. One, operating the street railways, has 35,000 kw. installed; the other supplies the larger part of the city's lighting and power and has 13,000 kw. installed. This latter plant is on the Annapolis Short Line about 1.5 miles from Baltimore. Each of these companies has an arrangement for receiving power from the Susquehanna development. Under these circumstances it was decided to purchase power. A contract, several features of which will be mentioned later, was entered into with the latter company whose plant lies on the line of the road.

Type of car. To meet the present daily passenger car mileage, single-car trains on one-half hour headway in the busier morning and afternoon hours, and on hourly headway at other times are proposed; through expresses and locals will alternate. A description of the car adopted is not necessary here, and may be had elsewhere. It may be stated, however, that it is of a type and design specially chosen to meet the demands of the required high-speed service. The center, intermediate and side sills are of steel. Wheels, trucks and couplers are according to M. C. B. standards. Train control is provided for both air brake and electric equipment. The car is of the Pullman type. The electric control is on one side of the vestibule and is enclosed at the rear end by a door, which when operating in the forward direction serves to seclude the motorman. The express car seats 62 passengers, is 55 ft. long, and the body alone weighs about 32,000 pounds. By multiple unit train control two-car trains on the above mentioned schedule will double the present car mileage. Moderate excursion loads may be handled with the equipment as installed. For possible concentrated loads steam will be relied on.

Available systems. In estimating the relative advantages of direct current and alternating current systems for the service, it was considered that the single-phase system is the only available alternating current system which has shown itself commercially successful in this country, and that the direct current system has no advantages so far as actual operating conditions are concerned. On the other hand the 1200-volt direct current system was not considered, since it does not offer a sufficient number of examples from which deductions as to operative success may be drawn. The choice of system was therefore based on a comparison of the available single-phase 25-cycle system and the 600-volt direct current system. This comparison was made from the standpoints of first cost and operating expenses; under the latter are included power consumption, station attendance and maintenance of equipment. As the physical differences in the two systems are not limited to the car and station equipments, but extend also to the distributing and return conductors, a somewhat detailed study of the effects in these two portions of both systems was made with special reference to the values of constants as given by several authorities. The constants for rail return and alternating current trolley drop vary rather widely in the literature of the subject. The following comparative figures are therefore not without interest. A note on the train resistance of single cars is also given.

DISTRIBUTING CONDUCTORS

Direct-current rail return. Owing to indeterminate values of the resistance of the paths of currents actually passing to earth, and of increased conductivity due to rail joints, the results of tests on contacts between bonds and rails and the values of bond resistance do not lead to reliable results when applied to the calculation of the resistance of rail return. Data from existing tracks are available however and show a rather wide difference of opinion as to permissible resistance of joint. Parshall and Hobart in " Electric Railway Engineering " place the resistance of " well-bonded track " at 5% greater than calculated continuous rail. One well-known road of this country replaces a bond if it shows a resistance higher than that of 3 ft. of rail, *i.e.*, about 10% of continuous rail, and tests on its track show the bond resistance to vary between 24 inches and 14 inches, or in the neighborhood of 6% of rail. Another conspicuous road places the defective limit as high as 5 ft. or 15% of continuous rail, with rails bonded to full capacity. The Electric Railway Test Commission Reports show that for single track laid in cinders and bonded to 17% of its conductivity the measured resistance is about 36% greater than the value for continuous rail. In this case, however, the bond was outside the angle bar and 30 inches long. The measured value is less by 3% than the calculated sum of rail and bond, even with contact between rail and bond assumed as zero. This indicates leakage to earth and increased conductivity due to rail joints. To estimate the resistance of the same track with bonds 12 inches long, a calculation was made assuming the 30-inch bond as one branch of a divided circuit, the other branch being the joint plates and stray paths. The resistance of the stray path was thus determined. For this track, then, bonded to 17% of its capacity with bonds 12 inches long, the resistance would be that of continuous rail plus 11%. Bonded to 34% of equivalent copper and with bonds 12 inches long, the resistance would be that of continuous rail plus 6.6%.

In view of the above we may take as attainable values of track return with 12 inch bonds the resistance of continuous rail plus 15% when bonded to 17% of the equivalent copper; the resistance of continuous rail plus 10% when bonded to 34% of equivalent copper; and when bonded to full capacity and under best conditions of maintenance the value may be as low as that of continuous rail plus 5%.

Alternating-current distributing conductors. We may conveniently consider the effects in trolley and track at the same time. When carrying alternating current the rails are the seat of reactance as well as resistance. Numerous tests have been made for determining their values. These tests differ somewhat, as the phenomena depend largely on the current density and on the shape of section and material of the rail. Perhaps the most pretentious tests are those of the Electric Railway Test Commission at St. Louis. It is to be regretted that these tests were not made on a track which conformed more nearly to present standards and were not more carefully prepared for publication. The report on this portion of the work presents many inconsistences and omissions; and a 30-inch 2/0 bond can scarcely be said to be common in practice. There is, however, much of value in the published account of the tests.

The drop in a single track of 56-lb. rails, and with the trolley 18 ft. above the rails at 25 cycles and 200 amps. is given by the Railway Test Commission as 122 volts per mile, with a total power factor of .60. The total reactance volts are about 97.6, of which 38.6 are due to the rails and ground, (as shown in a separate test) leaving 59 reactance volts per mile due to the field between trolley and track. The current density of 200 amperes has been chosen here for comparison of values since it represents approximately the maximum alternating trolley current which will be reached on the road under investigation.

Parshall and Hobart in " Electric Railway Engineering " give he following figures on page 285.

At 25 cycles, 4/0 trolley, 20 ft. above track

Impedance volts per 100 ampere per mile, 80 lb. rails = 76.5
" " " " " " " 60 " " = 75.3

These figures are higher than those of the Railway Test Commission. This is largely due to the large value of the ratio of alternating current to direct current drop in the track, Parshall and Hobart giving 8.1 and the Test Commission Report giving 5.5 for the same weight of rail. The sections of rails, however, are different and the current density is not given by Parshall and Hobart although this ratio depends largely on current density. That these large values of this ratio do not have a greater effect on the impedance of trolley and track is due to the comparatively high ohmic resistance of the trolley. Thus in the calculation given hereafter for 80 lb. rails the total drop at 160 amperes per mile at 25 cycles is about 64 volts, the direct current drop in the trolley would be 33 volts, and in the track 3.2 volts, giving as the ratio of alternating current to direct current drop for trolley and track about 1.85. Parshall and Hobart's figures indicate the small influence of the difference in weight of rail on the total impedance, although the impedance of the rails alone increases markedly with the weight.

One of the manufacturing companies places the drop per 100 amperes per mile in 3/0 trolley and 80 lb. track at 62 volts, height of trolley not stated. This figure is practically the same as that given by the Railway Test Commission for very different weight of rail and type of bond.

The above figures are at considerable variance. This is probably due in some measure to the difference in conditions of the several tests on which the figures are based. It is possible that the conditions in practice as dependent on the proportion of trolley current returned by the rails, may vary with the locality to a degree sufficient to account for the differences in the values of the voltage drop in trolley and track. It may not be without interest therefore to investigate by calculation the values to be expected.

The inductive component of the voltage drop is due to the aerial reactance and the reactance in the rail itself. The watt component is due to the resistance of trolley and track and to iron losses in the rails. The calculation is simple if all the return current be assumed to be in the rails and the values for rail iron loss be taken from published tests. The reactive volts at 25 cycles per mile of line of two wires of radius r and distance apart d, carrying current i in amperes are given by the expression $0.101\, i \log \frac{d}{r}$. One half of this value is due to each wire. We may take this expression as a basis for calculating the aerial reactance electromotive forces. Owing to the wide difference in nature of the overhead and return conductors we may consider them independently both as regards energy and reactance electromotive forces.

The most common type of trolley suspension for roads of the class here discussed is the single catenary. It is necessary to consider the influence of the suspension cable. Within the limits of accuracy of this calculation it will be sufficient to consider this cable as parallel to and at its average distance from the trolley wire. Let R_1 be the resistance per mile of the suspension cable, r_1 its radius, d_1 its distance above the rails, and i_1 the current flowing in it. The same letters with subscript 2 refer to the trolley wire. If i is the total overhead current, we have two equations for determining i_1 and i_2. We may conveniently use Steinmetz's symbolic method of notation

$$\underset{\cdot}{i}_1 R_1 - j\,.05\left(\underset{\cdot}{i}_1 \log\frac{d_1}{r_1} + \underset{\cdot}{i}_2 \log\frac{d_2}{r_2} - \underset{\cdot}{i}_2 \log\frac{d_1-d_2}{r_2}\right)$$

$$= \underset{\cdot}{i}_2 R_2 - j\,.05\left[\underset{\cdot}{i}_2 \log\frac{d_2}{r_2} + \underset{\cdot}{i}_1\left(\log\frac{d_1}{r_1} - \log\frac{d_1-d_2}{r_1}\right)\right] \qquad (1)$$

$$\underset{\cdot}{i}_1 + \underset{\cdot}{i}_2 = i \qquad (2)$$

The former equation expresses the equality in messenger cable and trolley of the total drop between station and car. Equation (2) expresses the total current as the vector sum of the currents in the two conductors. Solving we have:

$$\underset{\cdot}{i}_2 = \frac{i\left(R_1 - j\log\frac{d_1-d_2}{r_1}\right)}{(R_1+R_2) - j\left(\frac{\log\,(d_1-d_2)^2}{r_1\,r_2}\right)}$$

This expression does not contain either d_1 or d_2 explicitly, only the difference of these quantities appearing. Thus the division of current between trolley and messenger is independent of the height above the track. The effect of the field of the track current on this division is negligible for the values of d_1 and d_2 met in practice. For 3/0 trolley wire, and $\frac{7}{16}$ in. steel suspension cable we have $R_1 = 3.7$, $r_1 = 0.218$ in. $d_1 = 22.875$ ft., $R_2 = 0.326$, $r_2 = 0.205$ in., $d_2 = 22$ ft.
For $i = 100$ we have

$$\underset{\cdot}{i}_2 = 91.5 + j\,4.04;\ i_2 = 91.6$$

$$\underset{\cdot}{i}_1 = 8.5 - j\,4.04;\ i_1 = 9.4$$

Substituting these values in either side of equation (1) we find the drop per 100 amperes per mile in trolley and messenger cable is

$$\underset{\cdot}{E} = 30.58 - j\,32.76;\ E = 44.75.$$

This value will vary with the height of the trolley. The variation is small, however, if d_2 is above 20 ft, and formula (1) readily permits its calculation.

If the suspension cable is neglected as a conductor the value of the above drop is

$$\underset{\cdot}{E} = 32.6 - j\,36;\ E = 48.5$$

In considering the track return we face the uncertain distribution and value of its magnetic field, consequent aerial reactance, and the proportion of total current carried by the track. Assuming 100 amperes in each 80 lb. rail and assuming that the magnetic field outside the rail is the same as though all the current were concentrated at the center of the web, and applying the above expression for aerial reactance, we have as the reactance volts due to the field set up between track and trolley by the track current about 32 volts. This value takes due account of the mutual induction between the two track rails. The reactance volts within the two rails, as deduced from the results of the Railway Test Commission's tests on 80 lb. rails are 21. The total reactance volts in the track are thus 53, for trolley 22 ft. above track and total current 200 amperes. The ohmic drop in the rails and bonds is 6.45 volts; the component of rail drop due to iron loss is 22.4 volts (Cf. Report Rwy. Test. Comm.). The total watt component of drop at 200 amperes in the track is thus 28.85 volts. The electromotive force per mile per 100 amperes in the track is, therefore expressed by $E_t = 14.42 - j\ 26.5$. Adding this to the complex expression for the drop in the overhead conductors we have as the total drop $E_0 = 45 - j\ 59.26$, or $E_0 = 74.5$ volts per 100 amperes per mile. If all the current were carried by the trolley wire the value would be $E_0 = 47 - j\ 62.5$, or $E_0 = 78$. These figures also assume all of the return current to be in the track. This latter figure is remarkably close to that given by Parshall and Hobart, although the several components differ widely. Their value for the track is $7.7 - j\ 27$ and for the trolley $34 - j\ 37$. They have apparently not considered the secondary losses in the rails, nor the effect of suspension cable in reducing trolley reactance and resistance.

The numerous tables given by Parshall and Hobart showing the properties of rails and track as conductors for alternating current, indicate a very unfavorable comparison with the same properties when conductors of direct current. The basis of the tables is not definitely stated, however, and the values are not always in accord with published tests from other sources. To mention only one case, the drop per mile in 100 lb. rail carrying 100 amperes is given as 59 volts. The results of the Railway Test Commission give 41.5 volts for 80 lb. rail.

It is evident that in the particular case which we have considered the value arrived at is too high, for, as is well known, all of the return current does not flow in the rails. The results of an unpublished test of which the author has knowledge indicated the track current to be in places as low as 40% of that in the trolley, the average proportion being 50% or 60%. The conditions affecting this proportion vary so widely as to make it difficult to estimate the effect of this current dispersion on the reactance of the circuit. Let us assume, however, that p is the fraction of the trolley current in the rails, and that the iron losses and reactance within the body of the rail vary directly as the current at the low densities here used. (Cf. Report Railway Test Commission). Then the only indeterminate quantities entering into the value of the total drop in trolley and track are the reactance volts due to the trolley current as affected by the position of the mean path of the stray current in earth, the reactance volts due to the track current, and those due to the stray current. If for the purpose of investigation we make the not too violent assumption that the earth current distributes itself so as to be of circular cross-section tangent to the surface at the track, the first of these quantities increases and the last decreases with increasing radius of the circular section. The values of increased trolley reactance may be readily calculated from the right hand side of formula (1) by adding to d_1 and d_2 the value of the radius, R, of the assumed circular section of the stray current. The reactance volts due to the stray current are given by the expression:

$$\frac{0.101\, i\, (1-p)}{2} \log \frac{(22+R)}{R}$$

in which i is the total current and p the proportion of i carried by the rails. The other components of the total drop are either unchanged or directly proportional to p. The following table of values of total drop indicates how far the drop is affected by variations in the value of R and p.

Values of p.

Values of R	1	0.8	0.6	0.5	0.4
1	74.5	71.1	67.8	66.	64.4
2	74.5	70.9	67.	64.9	62.9
5	74.5	70.6	66.1	63.7	61.4
10	74.5	71.	65.9	63.3	60.8
50	74.5	72.9	67.8	64.9	62.5
100	74.5	76.	69.7	66.7	63.8

The effect of diminishing values of p, as was to be expected, is to decrease the total reactance. Increasing values of R first decrease, then increase the reactance. The stray current, if concentrated in a small section, has a magnetic field of appreciable value; consequently when the radius of section is small, increasing the radius causes rapid decrease in the field. For large values of R, however, the increased distance between trolley and resultant center of return conductor causes an increase in the total flux more than sufficient to compensate the above decrease. For all the values of p given the reactance volts are at a minimum in the neighborhood of $R = 10$. So far as the writer is aware there is no evidence as to the distribution of the stray earth currents. This distribution is in all probability never the same in any two cases. The amount of the stray current is obviously also a variable, not only with the particular case, but also with the proximity to feeding points. What is of interest, however, is that the reactance values vary very little within wide changes of both *R* and *p*, as is evident from the above table. Assuming the stray current to have a section of any radius between 10 and 50 ft., and *p* to be .5, the reactance volts per 100 amperes per mile are practically constant at 64 with a power factor .60. An increase from .5 to .8 as the proportion of trolley current in the rails changes this value scarcely 10%, while for smaller values of *R* the change is still less. With the assumptions stated the voltage drop per 100 amperes per mile at 25 cycles in 3/0 catenary trolley 22 ft. above track of 80 lb. rails is between 65 and 70 volts.

TRAIN RESISTANCE

There is wide diversity of statement and figures on the magnitude of train resistance. Two recent conspicuous comments on this subject also are found in the Report of the Railway Test Commission and in Parshall and Hobart's " Electric Railway Engineering ". In the following table the figures of these authorities are compared with those of Blood as given before the American Society of Mechanical Engineers, June 1903, and those of Armstrong (Trans. A.I.E.E., June 1903). The values given are for single cars.

Train Resistance—Pounds per Ton.

Speed miles per hour....	0	5	20	30	40	50	60	Single cars
Elect. Rwy. Test Comm..			12	15	20	26.8	35	38-ton car
Berlin-Zossen..........	15		3.3	7.7	17	15.4	18.3	90-ton and 77-ton car
Aspinall..............				9.4	12.7	17	22	90-ton and 77-ton car
Blood.................	5		9.7	13.5	18	21.9	29	38-ton car
Blood.................			9	12.3	16.1	20.5	25.2	50-ton car
Armstrong............	4	4.5	7.8	11.5	17	23	29	45-ton car

Parshall and Hobart conclude that Aspinall's formula gives reliable values for single car operation owing to their agreement with the results of the Berlin-Zossen tests. Aspinall's values for lighter cars do not change materially; for a 22-ton car at 50 miles per hour the figure is 16 lb. per ton. The figures are markedly less than those of the Railway Test. Commission. The heavy cars and excellent track conditions of the Berlin-

Zossen tests undoubtedly account for the low values, and values for lighter cars and average track may not be deduced from them.

The values given by the Railway Test Commission are distinctly higher than those in general favor, and should, therefore, receive attention. Without further corroboration, however, they must be accepted with some reserve owing to the variations in the figures in the several tests and to the unseasoned nature of the track.

It is evident that shortly after starting, the value of train resistance reaches a minimum somewhere about 5 lb. per ton. With 91.1 lb. per ton for a uniform frictionless rectilinear acceleration of one mile per hour per second, the necessary tractive effort after the actual moment of starting is about 96 lbs. per ton. The familiar and convenient figure of 100 lb. per ton thus allows about 4 lb. per ton for rotational acceleration, head wind and defective track conditions. It is evident also that during the acceleration period train resistance consumes only a small part of the total tractive effort and that errors in the values chosen assume no great importance for short runs. In this paper Blood's formula has been used for speeds of 20 miles per hour and upward and 100 lb. per ton has been assumed necessary for an acceleration of one mile per hour per second.

The Systems Compared

The basis upon which the choice of system was made has been already indicated. The proper capacity of available motor for the service was first determined for each type of equipment. To this end typical speed-time, current-time, and power-time curves for the average local run were plotted for 4-motor equipments with available motors of 75, 100 and 125 h.p. capacity as based on their one hour temperature ratings. The gearing in each case was made as low as consistent with the desired express schedule, since the conditions offered no special advantage in adpoting different gear ratios for express and local service. The methods of plotting these curves are familiar and require no comment for the direct current equipment. The treatment for the alternating current equipment during the period of acceleration is necessarily somewhat different and an outline of the method followed is given below. The typical curves for 100 h.p. alternating current and 90 h.p. direct current equipments were plotted, these motors showing themselves suitable on the basis of motor heating already mentioned. Speed-time, current-time, and power-time curves for each type of equipment were then plotted for every local run in each direction, due account being taken of curvature, grades, limited speed on bridges, etc. The results of this series of curves are given in the accompanying tables, together with their extension to the distributing system and power station. The value of this rather tedious process has been questioned. In the present case it not only afforded by comparison an indication as to the value of the typical curve for the purpose of computing an entire project, but it also enabled a run sheet to be constructed which developed passing points at rather different places than would have been indicated by the usual straight lines of schedule speed. The latter point is of particular value in a single track problem as determining which sidings should be equipped with trolley. After fixing the regular schedule sidings, a drop-back siding was provided in each case so as to prevent a loss of time being communicated to opposite traffic. This resulted in the fixing of eleven sidings, one of which is one mile long and another a half mile long, and there are three miles of double track at the Baltimore end. The total length of track thus becomes about 33 miles.

In the case of the alternating current equipment the construction of the speed-time and motor current-time curves is according to the usual methods, for the portion of the run after the period of uniform acceleration, *i.e.*, after the full voltage is on the motors. The initial portion of these and other derived curves does not, however, permit the simple determination possible with direct current equipments. As the literature of the subject presents little or no treatment at this point the following is offered as a simple method, which, from the data available, appears to approximate the actual conditions sufficiently closely for the purposes of calculation.

The motor current may be assumed as constant during the period of uniform acceleration at the value corresponding to the speed at which the acceleration begins to fall off. This conclusion is based on a study of the curves given by Bright (*Elect. Jour.* Vol. II, No. 11, p. 651, Nov. 1905) which, so far as the writer is aware, are the only curves taken from tests heretofore published. The motor current curves indicate a current rising slightly by steps during the period of constant acceleration to a maximum and beginning to decrease before the period of constant acceleration ends. An inspection of these curves shows that the average value of the motor current during constant acceleration is slightly less than the value corresponding to the termination of the initial straight portion of the speed-time curve. Thus, by area integration the average current per motor from start to stop in one of the runs measured by Bright is found to be 332.2 amperes. The value of this average, if the current during uniform acceleration is assumed constant at its value at the end of that period, is 335.6. The two corresponding values of the root mean square motor current from start to start are 412 and 416.

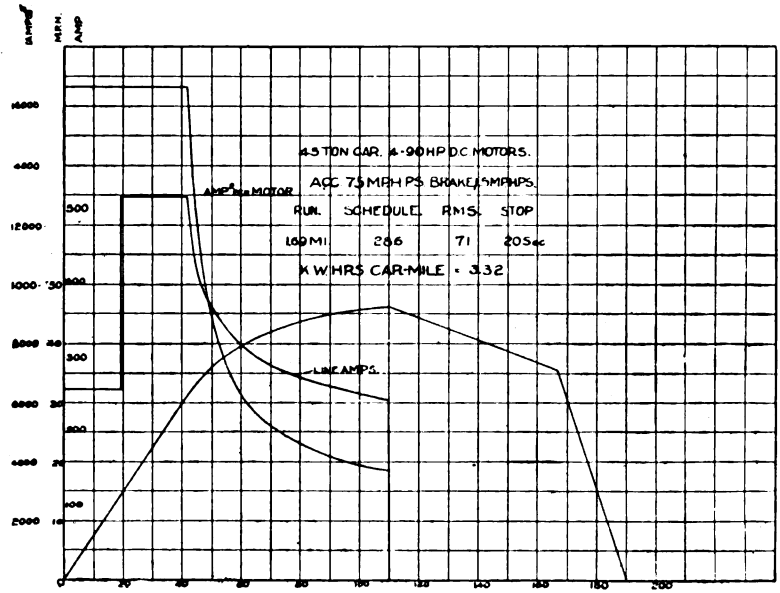
The initial portion of the line current curve will have a rising series of sharp changes corresponding to the voltage values of the several controller notches. The exact shape of this portion of the curve has no particular importance. The two aspects in which the line current must be considered are its maximum value as affecting line regulation, and the average value as determining the average apparent watts and the power factor. The maximum value is deduced from the maximum motor current and the ratio of line and auto-transformer voltages; it occurs then at the instant when full voltage is applied to the motors. The average value is found by the usual integration over its area, the average being taken for the period from start to cut-off. The shape of the initial portion should thus be considered in its effect on the area included by the whole curve. If, as already stated, the motor current is constant during this period, the starting value of the line current may be assumed as one-half its maximum value, since the motor voltage on the first notch is about one-half that on the last, a resistance automatically cut out limiting the first rush of current. The line current would then decrease slightly with increasing speed, increasing sharply at each controller notch. It may be safely assumed in calculation that a straight line between the above starting value and the maximum value gives the same area as the irregular curve just described. This suggestion is based on an inspection of the curves given by Bright and is sufficiently accurate, as the shape of this part of the curve affects the area only slightly in comparison with the remainder. The curve of motor kilovolt amperes is now determined. The line kw. at any instant is the sum of the useful mechanical output and the various losses. The mechanical output is the product of total tractive effort and speed, and when full voltage is on the motors is given directly by the motor curve of brake horse power with gears.

The losses to be considered are those in the gears and those due to copper and iron in motors, auto-transformer and car wiring. the losses in gears and motors are given by the curve of efficiency with gears. Those in the auto-transformer can only be determined from a knowledge of its characteristics. In the present case regulation and loss curves for the auto-transformer were furnished by the manufacturers. The values of the losses in the car wiring are here assumed as 1% of the total output. Following this method the portion of the curve for line kilowatts after full voltage is on the motors is readily plotted. The rising portion from the instant of starting, as in the case of the curves for motor current and line current, cannot be accurately predetermined owing to obvious indeterminate factors. Here, too, for the purposes of calculation it is sufficient to estimate its approximate form. Obviously the motor curve may not be used for the interval during which the motors are on the low voltage notches. The motor current, however, being approximately constant there, so is the net tractive effort, and the rise in speed being assumed to be uniform, the values of mechanical output are at once deduced and are seen to increase uniformly. At the instant of starting, the mechanical output is zero and the power drawn from the line is entirely dissipated in the transformer, wiring and motor. The voltage of the first transformer point is impressed on the circuit consisting of the starting resistance, the motor field and compensating winding and the stationary motor armature. The armature being stationary, there is a heavy loss in the short-circuit consisting of armature coil resistance leads and brush; this loss is of course greatest at standstill and decreases with increasing speed. The starting resistance also introduces a loss. In addition there are the normal copper losses in the remainder of the motor winding, the motor iron loss, and the losses of both types in the auto-transformer. The sum of these losses gives the initial value of the rising portion of the line power curve. It is manifestly impossible, and fortunately unnecessary, to determine this value accurately. We may note, however, that the value of the acceleration gives a value of the motor current, which as already stated, may with fair accuracy be taken as constant during this period. This current given, the motor and transformer curves give the normal losses when the motor is at speed, and thus a minimum value below which the initial line power cannot be. The increase due to starting resistance and armature coil short-circuit can only be known by a greater knowledge of the motor than is generally available. The line power curves in this investigation have their initial value as twice the minimum referred to. From this point a straight line has been drawn to the maximum value of power at the instant where the acceleration begins to fall off. Here, as before, a study of the curves of Bright is found to be corroborative. It may be emphasized again that the area comprised by this rising portion of the curve is for the usual type of run a sufficiently small part of the total to render error in the above assumptions of small effect. The curve of line kw. is thus derived, and with that of kilovolt-amperes determines the line power factor.

The results of the complete series of speed-time and other curves as given in the tables apply to a 37-ton car for the direct current and a 42-ton car for the alternating current equipments. There are also added in each case the figures taken from typical curves for the same cars. These typical curves were plotted for the same schedule speed derived from the complete set of curves. The results indicate that at the direct current car the average power consumption per car mile for the complete run is about 3.2% greater than shown in the typical curves. For the alternating current car the values of increase of complete run over typical run are 3.5% for kw-hr. per car mile. The typical run sheet therefore agrees very closely with the averages as deduced from the complete set. This is an interesting result, as the road is neither exceptionally straight nor level. The grades are generally up and down, and the two terminal cities are at virtually the same elevation. In the run which includes the Severn River bridge allowance was made for a reduction of speed to 10 miles per hour at the draw.

A continuous speed curve for the single-phase equipment was constructed for the express run between the terminals, with frequent coasts on grades, and a reduction of speed on the Severn bridge to 10 miles per hour. The average schedule speed was indicated as 42 miles per hour, the power consumption as 2.64 kw-hr. per car mile, and the average power-factor as 0.96.

In the case of neither of the cars above mentioned were the motors loaded to their continuous capacity. A later desire on the part of the management to increase the size of cars could, therefore, be met with the same motors, as is indicated by the figures in the tables for a 45-ton direct current car and a 50-ton


AMPS²
M.P.H.
AMP
45 TON CAR. 4-90 HP D.C. MOTORS.
ACC. 75 MPH PS. BRAKE 1.5 MPHPS.
RUN. SCHEDULE. RMS. STOP
169 MI. 28.6 71 20 Sec
K.W. HRS CAR-MILE = 3.32
AMP² PER MOTOR
LINE AMPS.
16000
14000
500
12000
1000 50 400
8000 40
300
6000 30
200
4000 20
100
2000 10
0
20
40
60
80
100
120
140
160
180
200

Fig, 1

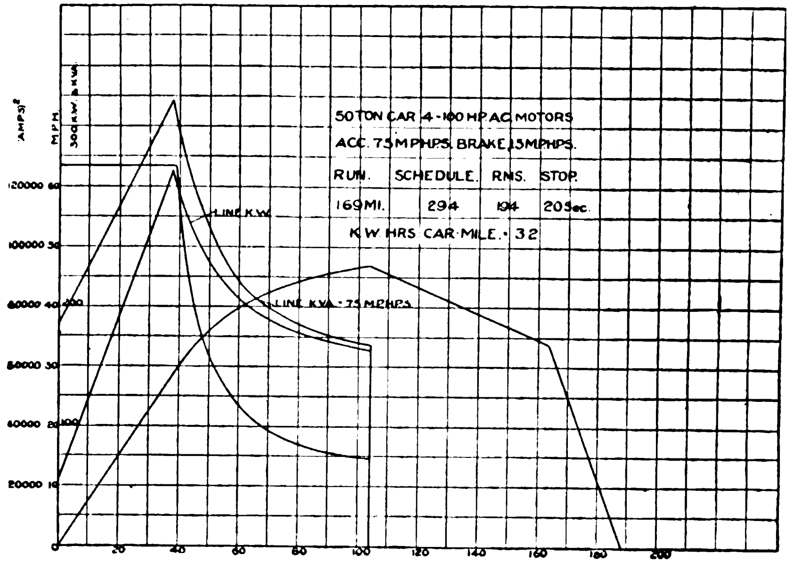
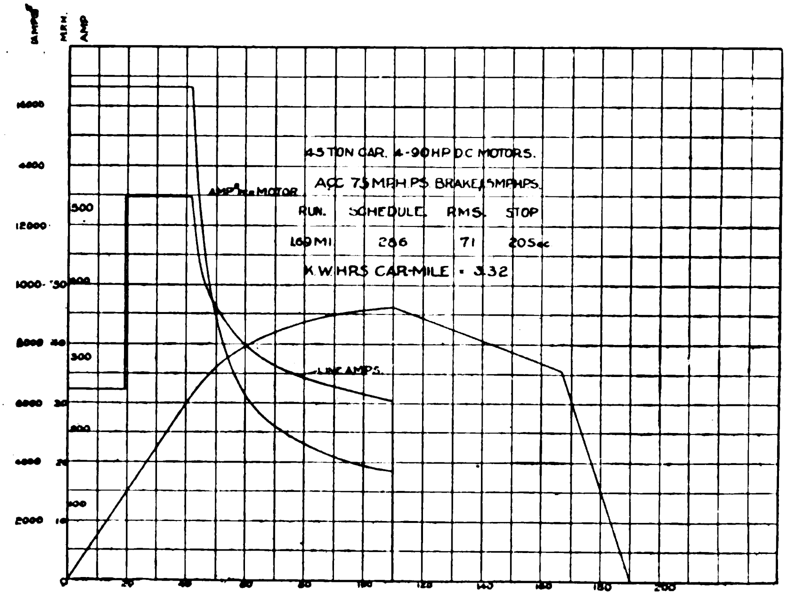

AMPS)²
M.P.H.
300 K.W. & K.V.A.
50 TON CAR 4-100 HP AC MOTORS
ACC. 75 MPHPS. BRAKE 1.5 MPHPS.
RUN. SCHEDULE. RMS. STOP.
169 MI. 29.4 194 20 Sec.
K.W. HRS. CAR-MILE. = 32
LINE K.W.
LINE K.V.A. = 75 MPHPS.
120000 60
100000 50
80000 40 200
60000 30
40000 20 100
20000 10
0
20
40
60
80
100
120
140
160
180
200

Fig. 2


AMPS²
M.P.H.
AMP
14000
4000
12000
1000 50
8000 40
6000 30
4000 20
2000 10
500
400
300
200
100
0
20
40
60
80
100
120
140
160
180
200
45 TON CAR. 4-90 HP DC MOTORS.
ACC 75 MPH PS BRAKE 15 MPHPS.
RUN. SCHEDULE. RMS. STOP
169 MI 286 71 20 Sec
K.W. HRS CAR-MILE · 3.32
AMP² PER MOTOR
LINE AMPS.

FIG, 1

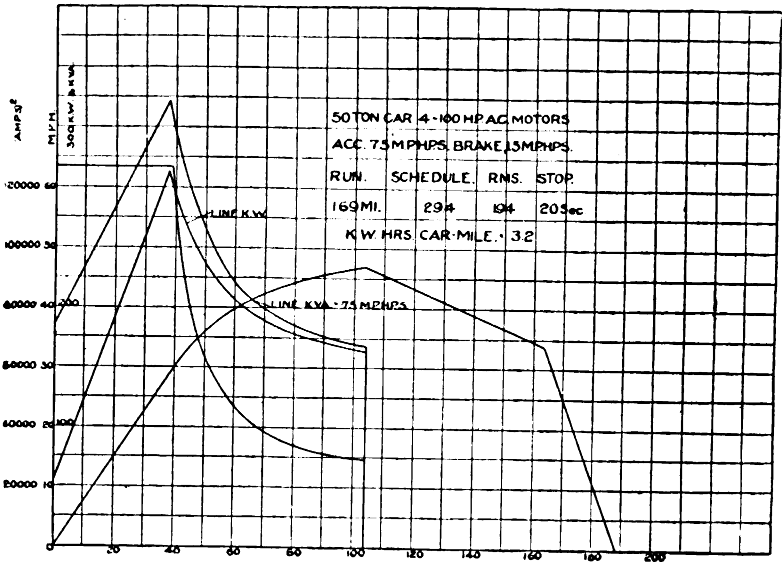

AMPS)²
M.P.H.
300 K.W. & K.V.A.
120000 60
100000 50
80000 40 200
60000 30
40000 20 100
20000 10
0
20
40
60
80
100
120
140
160
180
200
50 TON CAR 4-100 HP AC MOTORS
ACC. 75 M.P.H.P.S. BRAKE 1.5 M.P.H.P.S.
RUN. SCHEDULE. RMS. STOP.
169 MI. 294 194 20 Sec
K.W. HRS. CAR-MILE. · 3.2
LINE K.W.
LINE KVA · 75 MPHPS

FIG. 2

alternating current car. These figures are taken from the typical curves shown in Figs. 1 and 2. In view of the reliability of the typical curve as above indicated, the comparison of the two systems is based on these curves, due regard being had to the small percentage increases already mentioned. The comparative figures are given in the following table.

Type of car	Schedule speed	Kilowatt-hours car-mile at car	Kilowatt-hours car-mile at sub-station
37-ton direct current from complete runs	30.3	2.85	3.58
37-ton direct current from typical curves	30.3	2.76	
42-ton alternating current from complete runs	30.3	3.27	3.31
42-ton alternating current from typical curves	30.3	3.16	
45-ton direct current from typical curves	28.6	3.32	
50-ton alternating current from typical curves	29.4	3.2	

A further fact to be noted from a comparison of the two typical curves is that the alternating current car requires less power consumption for the run in spite of its greater weight. The two values of kw-hr. per car-mile are 3.2 and 3.32. This is due to the series resistance losses in the direct current car; owing to the short length of the run the motors are on resistance more than one-third the time during which power is applied. The maximum power reached for the single-phase car is greater, and so also is the power throughout the period when the motors are on full voltage. The former is, however, applied for a comparatively short time, and the direct current power is applied longer owing to the lesser value of maximum attainable speed. This difference does not obtain in the runs for the lighter cars. The direct current equipment on a 37-ton car accelerates with less demand and cuts off earlier than the alternating current equipment on the 42-ton car. Increasing the sizes of car to 45 tons and 50 tons imposes less additional demand on the single-phase motor than on the direct current motor of lower rating. The latter motor on the 45-ton car is worked well up to its figure for continuous rating, and it is questionable whether or not it is sufficient for the service. If the conclusions of the investigation pointed less strongly to the single-phase system, it would be necessary to consider a larger direct current motor before reaching a conclusion.

Increasing the figures for power by the percentages given above we have for values of kilowatt-hour per car-mile at the car, for the 45-ton direct current car 3.43 and for the 50-ton alternating current car 3.32.

The weights of the two cars are distributed as follows:

	Alternating current.	Direct current
Car body	32,000 lb	32,000 lb.
Trucks	21,000	21,000
Motors and control	32,000	22,500
Air brakes	3,000	3,000
Live load	9,000	9,000
	97,000	87,500

STATION EQUIPMENT AND POWER CONSUMPTION

Single-phase system. In the alternating current system the starting current per car, assuming that the rate of acceleration is constant, varies with the track conditions. On level track the line current per car at 6600 volts is 57 amperes at 0.75 miles per hr. per sec. and 70 amperes at 1 mile per hr. per sec. at a power factor of 0.80 or better. Assuming the use of the available 3/0 catenary construction, and the voltage drop per 100 amperes per mile as 70 with a power factor 0.60 and a maximum permissible drop of 10%, it is evident that a two-car train may accelerate at 1 mile per hr. per sec. when fed by a single trolley at a distance of about 6.75 miles. The schedule is based on an acceleration of 0.75 miles per hr. per sec. and the equipments chosen will operate satisfactorily at considerably greater values of drop. The bunching of cars in such a section should therefore offer no difficulty on this score. A substation was located at a convenient station 6.25 miles from Annapolis and 17.4 miles from Westport. Using the figures already given, two cars starting at Annapolis at 0.75 miles per hr. per sec. will cause a maximum drop of 7.6% when fed from this substation. The line impedance at power factor 0.60 increases the reactive component of the car demand but slightly. If the car power factor be taken as low as 0.80, the load at the substation has a power factor 0.78.

Considering the resort Bay Ridge, 4 miles from Annapolis, the substation might with better advantage be located nearer Annapolis. This would, however, increase the starting drop in the region between power house and substation. As single cars may be readily started at Bay Ridge when fed over the above distance, and as the equipment of this branch is as yet undetermined, this question is of little importance. Future extension to Bay Ridge may be accomplished by an extension of the transmission line and the installation of a temporary or portable transformer substation. The above location of the substation as one trolley feeding point and the powerhouse as another meets the requirements of regulation satisfactorily.

The power house at Westport, 1.6 miles from Baltimore, as the feeding point for the north half of the line, although not located to the best advantage from the standpoint of symmetrical feeding, saves the building of a second substation. An effort was made with the power company to permit the load to go directly on the station bus through two-phase three-phase transformer connection. This would result in an average uniform distribution of load on the three-phases, but also in possible short applications of large fractions of the total load on one phase. The form of contract permits this, but the power company's distaste for unbalancing is shown by a further stipulation that the maximum demand shall be reckoned as three times that on the most heavily loaded phase. As the total installed capacity in the powerhouse is 13,000 kw. and as the maximum starting demand of the normal daily schedule may reach 1800 kilovolt-amperes, this attitude is not to be wondered at. It is increasingly evident that there are few cases where a single-phase railway, with the usual erratic combinations of starting peaks, may be supplied from a system furnishing at the same time light and power for other purposes. None of the polyphase-single-phase transformations recently reviewed by Armstrong (Proc. A.I.E.E.) will prevent occasional excess demands on one phase. Also some of these methods have the additional disadvantage of largely increased reactance drops with unbalanced loads. The problem narrows down to isolated generators for the railway load, or motor-generators for distributing the load uniformly, whatever its value. The former alternative was out of the question in the present instance, the units in the powerhouse being 2000 kw. each. It is, therefore, evident that the adoption of the single-phase system for this road meant the building of its own power plant or the installation of motor generators.

Aside from the question of efficiency, the motor generator is not attractive when power is purchased, since power contracts always have their limit of life. In Baltimore, however, as already mentioned, there are two large plants of similar voltage and frequency characteristics, and the Susquehanna development will also deliver power there in the same form in the near future. The likelihood of having the motor-generators left without a proper source of power is therefore remote.

The power and distributing system for single-phase equipment then resolves itself as follows; synchronous 13,000-volt 25-cycle 3-phase motors direct-coupled to 6600-volt 25-cycle single-phase generators. The trolley is fed directly from the generators, as are also step-up transformers for the 17.5 mile transmission to the substation.

The starting demand of a car varies between 375 and 475 kilovolt-amperes depending on the grade. Normal half hourly traffic requires four cars on the line at one time, with the possible bunching of three cars on one substation, or about 100% overload for two 300 kw. transformers. Three such units in the substation, and space and wiring for a fourth, will provide reserve capacity and provision for future expansion. The same transformer capacity is installed at the powerhouse. Excursion traffic should be handled by two car trains at lessened headway. Such trains would accelerate at a low rate. The running of nine trains on a 15-minute headway means a minimum of six on the line at once to preserve opposite traffic. The sustained demand if these trains are single cars will not exceed 1600 kilovolt-amperes. Two two-car trains and a single car starting at the same instant would impose 150% overload on three 300 kw. transformers. The motor generators obviously take the whole load. The sustained excursion demand above mentioned would be about 25% overload for 1200 kw. in motor generators. Three 600 kw. units will provide ample reserve and provision for considerable future growth.

For the comparatively short transmission distance there is no decided advantage in increasing the voltage above 22,000. If 33,000 volts is chosen, the size of wire is reduced to a point inadvisable from considerations of tensile strength and the difficulties and cost of insulation are also increased. Two transmission lines each of two No. 2 B. & S. wires 30 in. apart, and both lines carried on the same cross-arm, provide interchangeability and reserve capacity. With a load of 800 kilovolt-amperes at power factor 0.85 on two substation transformers, the drop between the power house 6600-volt bus and the substation trolley connection will be about 15%; the power factor at the station will be about 0.82. From the tabulated results of the complete local runs, the average efficiency of trolley and track is better than 98%, as shown by the values of kw-hr. per car mile at the car and at the substation. The loss was calculated by assuming that the average line current during the period while power is applied, is fed to a point one-third through the particular run in question. If the value of root mean square line current for the typical run is assumed to be delivered at the average distance of a car from a substation, the trolley and track loss is somewhat over 1.5%. In calculating these losses the energy component of track and trolley impedance as already given has been used. Assuming the average efficiency of the transformers at 96.5% and calculating that of the transmission line at 98%, we have half the total power supplied through the substation at about 89% and the other half fed directly to the trolley from the generator bus-bar at 98%. For the normal schedule already described the daily power consumption would be as follows:

22 locals at 3.32 kw. hr. per car mi.	1840 kw-hr.
20 expresses at 2.85 " " " "	1401 " "
	3240

One half of this at 98% and one half of 89% gives 3475 kw. hr. at the generator bus-bar. At an average motor generator efficiency of 80% we have 4350 kw-hr. daily consumption for the proposed normal schedule under the single-phase system.

Direct-current system. The normal starting current of the car described above for the direct current system at an acceleration 0.75 miles per hr. per sec. is 516 amperes; for a two-car train approximately 1000 amperes will be taken at starting. With two cars starting and one running the demand may easily go to 1200 amperes. Assuming a maximum permissible drop of 25% and 600 volts at converters and supposing that the single 80 lb. track is bonded to full capacity (0.028 ohms per mile), something more than 2,000,000 cm. of copper would be necessary to supply 1000 amperes to a two-car train starting from Annapolis from a substation 3 miles away. Aside from the consideration of the cost of copper, however, the question of collecting the large current values, and the high speed to be reached, points at once to the third rail as the proper method of feeding. Assuming 80 lb. third rail bonded to 10% of equivalent copper as having a resistance of 0.044 ohms per mile, we have as the resistance of the third rail and single track 0.076 ohms per mile. With 600 volts on the third rail and a 30% drop, this will permit a distance of somewhere between two and three miles as the length of the end of the feeding system beyond the last substation. Assuming that two cars in starting take 1000 amperes, and that they will make the only demand on the end beyond the substation, it would be possible in the present instance to locate a substation at a convenient passing point, indicated by the proposed schedule, 2.8 miles from Annapolis. The northernmost feeding point would naturally be the Westport power house. The distance between these two stations would thus be 20.85 miles. Considering the possibility of operating with only one intermediate substation, it is to be noted that the distance between substations would then be approximately 10.5 miles. With three cars starting midway between two substations, which would be a common occurrence, the drop would be approximately 300 volts. This figure assumes also very low values for track resistance. On the above basis it is therefore inadvisable to attempt to operate with less than four substations. These would be located as follows: one at Westport, one at Winchester (2.8 miles from Annapolis) and two others between these. The greatest distance between substations would thus be 7 miles. With three cars starting midway between two substations the drop would be about 200 volts. It is worth noting that if the road were double tracked it would be possible to obtain satisfactory regulation with two substations.

In the matter of substation capacity, when the demand on one substation is that of two cars starting and one running, the demand is in the neighborhood of 760 kw. With three starting on one substation, the demand is 920 kw. At 100% overload the latter figure would necessitate 460 kw. capacity. Thus one 300-kw. converter would take care of the normal single car schedule, and two 300-kw. units in a substation would handle a schedule involving two-car trains in one direction, and would, therefore, constitute a certain spare capacity when considered from the standpoint of the normal single-car schedule. This reserve is, however, not so great as that allowed for the single-phase system. For the transmission line, if a resistance drop of 5% be allowed, the average normal load can be handled by a 22,000-volt, three-phase line of three No. 3 B. & S. wires.

From an inspection of the results of the complete set of run sheets it will be noticed that the efficiency of trolley and track has an average value of about 80%. This was, however, based on three substations and a smaller value of conductivity in the distributing system, thus obtaining less first cost at the expense of regulation. Taking the mean distance of a car from a substation as one quarter the distance between substations, and assuming the resistance of third rail and track as 0.086 ohms per mile, the car will be fed over a resistance of 0.114 ohms. The R M S line current for the typical run is 351 amperes. Using these figures the efficiency of trolley and track is in the neighborhood of 92%. The single ends beyond the extreme substations are not included in this value which may be considered high. Taking the efficiency of converters and transformers at 90%, of the transmission line at 95%, and the average efficiency of powerhouse transformers at 96.5%, we would have a resultant efficiency somewhat less than 76%. About three quarters of the total load would be supplied at this figure—one quarter would be supplied directly from the powerhouse at 82.8%.

On the above basis the average daily consumption of power for the normal schedule would be as follows:

22 locals, or 555.5 car miles, at 3.43 kw-hr. = 1900 kw-hr.
20 expresses, or 505 car miles, at 2.7 kw-hr. = 1363 kw-hr.

Of this total of 3263 kw. hrs., figuring three quarters at 76% and one quarter at 83%, we would have about 4200 kw. hr. as the average daily consumption under the direct current system.

Choice of System

For the purpose of making a choice of system it is only necessary to consider those particulars in which the two systems differ. The most important of these are first cost and operating expenses, the latter including power consumption, station attendance and maintenance of equipment. Following is a comparison of the cost of the essential parts of the two systems, as outlined above, and for the most part based on prices asked from manufacturers to cover the specific cases. The copper was bought during the high market of 1907. This fact has no particular weight in throwing the advantage to either system, if the direct current system includes the third rail as conductor. The cost of the third rail is based on a comparison of the several estimates compiled by Gottshall in " Electric Railway Economics ". The length of track, trolley and third rail is taken as 33 miles to include the double tracks at the north end and middle of the line and the sidings. The transmission line is about 3.4 miles longer for the direct current than for the single-phase system, and the figures for this item include poles. Converters with transformers are valued at $17.50 per kilowatt.

	Direct current	Alternating current
9 cars completely equipped	$107,300	$149,300
Catenary trolley, poles, wire and guys		75,000
Third rail	132,000	
Transmission line	65,000	36,000
Powerhouse apparatus	21,000	62,000
Substation "	39,000	8,000
Substation buildings	15,000	3,000
Bonding	18,000	11, 00
	$397,300	$344,300

In power consumption the two systems appear to be on an equal footing. This is rather surprising since the motor generators reduce the efficiency of the single-phase system very markedly. In this case this reduction is offset by the losses in rotaries, the excess loss in distributing system, and the increased power consumption at the car, due to the smaller motors and short runs. For longer local runs the single-phase power would go to higher values than that for the direct current system. The price of power is based on the maximum demand and the total consumption, and for the normal schedule would average about 2.3 c per kw-hr. The monthly excess of single-phase power would thus be about $100.

In the matter of station attendance the direct current system would require that of three substations, which have no counterpart in the single-phase system. Two men per station at $75 per month each would make this item $5400 per year.

The cost of maintenance and repairs of car equipments would be less in the direct current system. Recent figures indicate that 0.5 cent for direct current and 0.75 cent per car-mile for alternating current is a fair basis for comparison. At 30,000 car miles per month the excess of this item for alternating current operation would be $900 per year. These items represent the principal particulars in which the two systems would differ. Other less conspicuous differences may be embraced for the purposes of this comparison in a figure of 10.5% for fixed charges on the initial cost. This item presents then an advantage on the part of the alternating current system of $5565 per year.

Summarizing the above items, we find a total of $8,865 per year in favor of the alternating current system. The figures for cost of the alternating current equipment have been taken for the most part from prices actually paid for construction and apparatus, while those for the direct current system are estimated. The result is that there are several advantages possessed by the alternating equipment as installed which would represent a considerable increase in the figures for first cost and operating cost, if obtained under the direct current system. The equipment as installed provides considerably more substation and power station reserve capacity than was estimated for the direct current system. It provides for the possibility of feeding moderate loads at Bay Ridge, and increased feeding capacity to that point at moderate cost. To accomplish this with the direct current system would mean a considerable addition to the equipment as outlined. The regulation of the system as installed is better than that available with direct current. The schedule speed is somewhat better, or to express it differently, the initial cost of the direct current equipment should be increased by an amount necessary to cover a motor of capacity equal to the alternating current motor. No attempt has been made to evaluate the cost to the alternating current system of these several advantages.

COMPARATIVE COSTS OF STEAM AND ELECTRICAL OPERATION

The company's statements of operating expense under steam were available for a period of several years. They are sufficiently detailed to invite an attempt at a comparative estimate of the cost of electrical and steam operation. The difficulties in the way of such an estimate are well known. In the present case the nature of the service is to be changed both in frequency and the size of units. The extent of these changes cannot be predetermined. The exact proportion of old rolling stock necessary to maintain the present schedule, and the proportion of new equipment, both in rolling stock and station apparatus, necessary to operate on an equivalent new schedule can only be roughly estimated.

In the following comparison the present normal steam schedule is assumed to require four locomotives and fifteen coaches. Under this schedule the maximum number of trains on the line at one time is two and a train averages three coaches; there are, however, occasional special trains. Under electricity the proposed maximum number of cars on the line at once for equivalent normal schedule is four, and the necessary charges are based on these assumptions. The operating expenses for a typical nine months of steam operation are given below; the only items discussed are those peculiar to steam operation.

Conducting transportation	$43,366.49
Maintenance of way	22,129.46
Maintenance of equipment	12,159.08
General expenses	12,196.91
	89,851.94

The car-mileage during this period was 277,754 or 30,861 car-miles per month. The cost per car mile is thus 32.36 cents. The proportions of the above figures peculiar to steam operation are indicated as follows:

Conducting transportation.

Fuel	$13,692	
Waste, water, and oil	1,114	
Trainmen	11,776	
Roundhouse men	354	
	$26,993, or	9.71 cent per car-mile

Maintenance of Equipment.

Repairs to locomotives	2.13	cent per car-mile
" " coaches	1.76	" " " "
Maintenance of way	7.97	" " " "
Interest on equipment peculiar to steam operation, including locomotives, coaches, 2 water plants turn-table, coal plant, etc	1.52	" " " "
The total of these items is	23.1	" " " "

Each of the above items will be modified under electrical operation approximately as follows, the same car mileage being assumed:

Conducting Transportation.

Power, 1060 car miles per day	7.86	cent per car-mile
Trainmen, 7 crews of 2 men	3.90	" " " "
Signalmen and dispatchers	.5	" " " "

Maintenance of Equipment.	
Repairs to cars and equipments	2.76 cent per car-mile
Transmission line, 3% of cost	.3 " " " "
Trolley 5% of cost	1.02 " " " "
Station equipment 3% of cost	.4 " " " "
Maintenance of way	7.25 " " " "
The proportionate change in this item is based on the figures given by Stillwell and Putnam; as given here, bonds are included but not overhead construction.	
Interest on Equipment	
Eight cars, power apparatus, trolley and transmission line and bonding	4.48 cent per car-mile

The total of these items is 28.47 cent per car-mile, or an increase of 5.37 per car mile over the present figure for steam operation. This increase therefore represents an increased total operating cost of electricity over steam of about 16.6%.

Considering the possibility of compensating for the above increase in operating cost, it may be noted that during the last ten years the passenger traffic of the road has shown a consistent increase, amounting on the average to about 5.5% for the past year. There was therefore a large rate of increase in the earlier years of this period. Much of this increase must be attributed to the legitimate results of the facility of travel afforded by the increasing efficiency of the steam road. In spite of the persistence of the increased receipts from year to year a discussion with the management reveals a decided idea that the through traffic is about fixed in value. Notwithstanding an increase due to improved service the reduction in rates consequent upon competition is regarded as an offset such as to maintain the through traffic at a constant value.

As suggested before in this paper, it is to the local traffic that an increase of earnings is looked for. At present the earnings from local traffic represent about 25%. The ratio of operating expense to earnings is about 65%. With the above increase of operating expense and assuming no increase of traffic, the ratio of operating expense to earnings is increased to about 76%. It is only necessary, however, to assume that the local traffic will double, to reduce the ratio of operating expense to earnings to less than its present value. As there is practically no competition in local traffic, the results of frequent electric service in other localities indicate that such an increase in local traffic in this instance is not improbable.

It would seem, therefore, that considering passenger traffic alone, notwithstanding the fixed charges on the investment, on a road with traffic of the nature indicated in this case, the substitution of electricity for steam is well worth considering.

CONCLUSION

Outlining briefly the results of the discussion in this paper, there may be mentioned besides the general description of the road and the considerations leading to the adoption of electricity the following:

1. A review of the values of impedance of the circuit consisting of trolley and track, and a method for calculating the same.
2. Several suggestions as to the methods of constructing current and power curves for single-phase equipments.
3. A discussion as to the accuracy of the typical run curve in its application to the results to be met in the entire series of runs.
4. An indication that in some cases the use of motor generators with the single-phase alternating current system does not preclude its comparing favorably with the direct current system of 600 volts.
5. While no general conclusions may be drawn from individual cases in the substitution of electricity for steam, the indications in the road here described are that, on the basis of passenger traffic alone, the undertaking will prove a profitable one.

A paper to be presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., June 29–July 2, 1908.

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APPLICATION OF FRACTIONAL PITCH WINDINGS TO ALTERNATING-CURRENT GENERATORS

BY JENS BACHE-WIIG

Fractional pitch windings have been treated by various authors in the past, especially with regard to the influence they have upon the self-induction of the armature winding. The object of this paper is to deal briefly with the points leading to the use of a chorded winding for alternating-current generators from the standpoint of manufacture and design, and to indicate the influence this winding has on the performance of a machine.

Reasons for chording the winding. In general, the chorded winding has been adopted to facilitate the manufacture of armature windings. As generators are manufactured, there are certain standard frames used for a number of ratings at different speeds and voltages. Group windings, with the number of slots per pole per phase equal to an integer, are generally preferred, and the number of conductors is fixed within a limited range for a given voltage. This often necessitates the use of a chorded winding in order to get the proper effective number of conductors. This is especially the case for low-voltage machines of large size. Further, a winding often works out in such a way that a better arrangement of conductors in the slot can be obtained through chording. A two- or a four-pole high-speed generator is another example where the chorded winding facilitates manufacture. Such a machine will naturally have a comparatively small bore, and if open slots and form-wound coils are used, it is impossible with a coil-throw equal to the pole pitch to bring the coil through the bore of the armature without bending it entirely out of shape. The only solution, therefore, is to chord the winding a sufficient amount to allow it to pass through the bore. In this case, therefore, the chorded winding is of great advantage, as it permits the use of form-wound coils. This may not hold in cases where the coils are made in halves.

With regard to the construction of the end-connections of form-wound armature coils for large alternating-current generators, especially for a generator with a small number of poles, the space occupied by the end-connections is considerably smaller for a chorded winding than it is for pitch, even taking into account the increased number of armature conductors made necessary by the chord. The effect of chording upon the number of armature conductors is to increase the number in the ratio of the sine of half the electrical angle between the two sides of the coil, whereas the length of the end-connection and the distance the coils build out decreases directly in proportion to the electrical angle. The result is a saving in space. This is of particular benefit to all two-pole machines, but applies also to four- and six-pole machines above 500 kw. It may also be of advantage to chord the winding for these reasons for smaller machines when wound for high voltage.

Take, for example, a 300-kw. 11,000-volt three-phase 500-rev. per min. 25-cycle generator. This machine has six poles, and with six slots per pole per phase will have 108 slots total. Having form-wound coils with the coil-ends extending in a parallel plane to the shaft, one coil per slot, and a pitch winding (1 and 18) the distance between the armature iron and the extreme end of the coils is approximately 16.5 in. Between adjacent coils 0.25 in. air space is provided. Chording this winding down to 1 and 14, or 130 electrical degrees, reduces the above distance to approximately 14.9 in. or decreases the width of the machine 3.2 in. The same winding arranged for two coils per slot, builds out approximately 20.5 in. for pitch winding and 16.75 in. for throw 1 and 14. This means a 7.5 in. reduction in all-over width of the machine. The width of the armature iron being 8 in., it can readily be seen that this insures relatively large saving in space. As indicated by the above dimensions, the winding with two coils per slot extends farther beyond the armature core than does the winding with one coil per slot, and, accordingly, chording the winding is more advantageous for a two-coil-per-slot winding.

As stated above, space can be saved in the way the coils build out even for a six-pole, 300-kw. machine. As space is saved, the mean length of one armature turn is reduced. On the other hand, the number of conductors on the armature is increased, and thus a certain throw will give the most efficient winding in regard to copper loss and amount of copper. Taking the above mentioned 300-kw. generator and working it out on the basis of equal iron losses, with one coil per slot there is practically no difference in the weight of copper with different throws—the decrease in length of mean turn is balanced by the increase in the number of turns. With two coils per slot there is a saving of approximately 25% in the weight of copper and of copper loss in favor of the chorded winding having coils lying in slots 1 and 14 over the pitch winding having coils lying in slots 1 and 19. The gain by reducing the throw, therefore, amounts to gaining space for the one-coil-per-slot winding only, and means a saving in space and a reduction in copper loss and weight of copper as well for the two-coil-per-slot winding.

As mentioned above, the winding with two coils per slot builds out farther than does the winding with one coil per slot, and the comparison between the pitch winding and the chorded winding will, therefore, show up more in favor of the winding with two coils per slot.

As the six-pole 300 kw. generator here referred to is a comparatively small machine, it is evident that for large generators, or generators with a smaller number of poles, the above figures will show up still more favorably for the chorded winding; the example indicates that even down to this size of machine it is advantageous to chord the winding.

One may say that chording the winding is to take the copper out of the end-connections and put it in the slots, which is another point in favor of the chorded winding, for it is easier to get rid of the heat in that part of the coil which is imbedded in iron than it is to cool the end-connections of the winding. The ventilating conditions, therefore, are often improved by chording. As above stated, this applies particularly to large machines and windings having a comparatively large throw.

It is stated above that the length of the end-connections decreases in proportion to the chord and that, even if the weight of the copper is not decreased, the chording has the effect of decreasing the amount that the coil-ends build out. As the question of bracing the coil-ends of a generator with a small number of poles and a large throw is of great importance, it will readily be seen that shortening the end-connections is a great benefit in this respect; it makes them stiffer, so that even if coil supports are used, both in the case of pitch winding and chording, the chorded winding is superior in mechanical strength.

It may be argued in connection with the above that a chorded winding requires heavier insulation of the end-connections than does a pitch winding as the phases are intermixed and points of higher potential are brought together. As a rule it is true that a chorded winding, will have more points of higher potential between adjacent coils than will a pitch winding, but considering that the coil-ends for larger generators always should be arranged with an air-space between adjacent coils, and further that they are braced and prevented from touching one another, in only extreme cases will it be necessary to provide for any extra heavy insulation. In an ordinary pitch winding, points of high potential are brought together at the beginning of the phases. As a rule no extra heavy insulation is provided for at such points. Considering the part of the coil lying in the slot, even if the full-line voltage exists between two coils in one slot, it should not cause any trouble as each coil is already insulated against ground.

The effect of chorded winding upon armature reaction. As, for a given voltage, the effective number of turns must be the same whether the winding is pitch or chorded, the effective number of armature ampere-turns is also the same in both cases; consequently the demagnetizing effect will remain practically unchanged. The chord, however, has an influence upon the self-induction of the machine. This effect is very much the same as in the case of an induction motor, a subject considered at length in a paper read before the Institute.* The reducing in-leakage, and the coil-end leakage, as pointed out in that paper, could be applied to similarly wound alternating-current generators. In many cases, however, the self-induction does not have much influence upon the short-circuit ratio, as it is small compared with the demagnetizing ampere-turns, and, consequently, a change in self-induction will not change the short-circuit ratio to any extent, so that in ordinary cases the self-induction can be figured without considering the chord. There are cases, however, where the decrease of the self-induction due to the chording of the winding has to be carefully considered. One

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* Fractional Pitch Windings for Induction Motors, by C. A. Adams, W. K. Cabot and G. A. Irving, Jr., Niagara Falls, June 28, 1907.

fluence of the chording upon the slot leakage, the tooth-tip such case is when a delta connection is used for a three-phase generator with chorded winding with two coils per slot. It is a well known fact that when the wave-form is not a sine, the higher harmonics present in such a winding cause currents to flow round the delta. In most cases these currents are small and the loss due to them is negligible. This, however, does not hold in the case referred to; for as the same current flows in the three legs of the delta through all the coils in succession the slot and the tooth-tip leakage is eliminated for those slots in which the current flows in opposite directions, thus reducing the self-induction of the circuit. The self-induction, however, is the main thing that opposes the flow of this current, and thus it can easily be seen that when the chording of a delta-connected winding is carried too far excessive internal currents may be

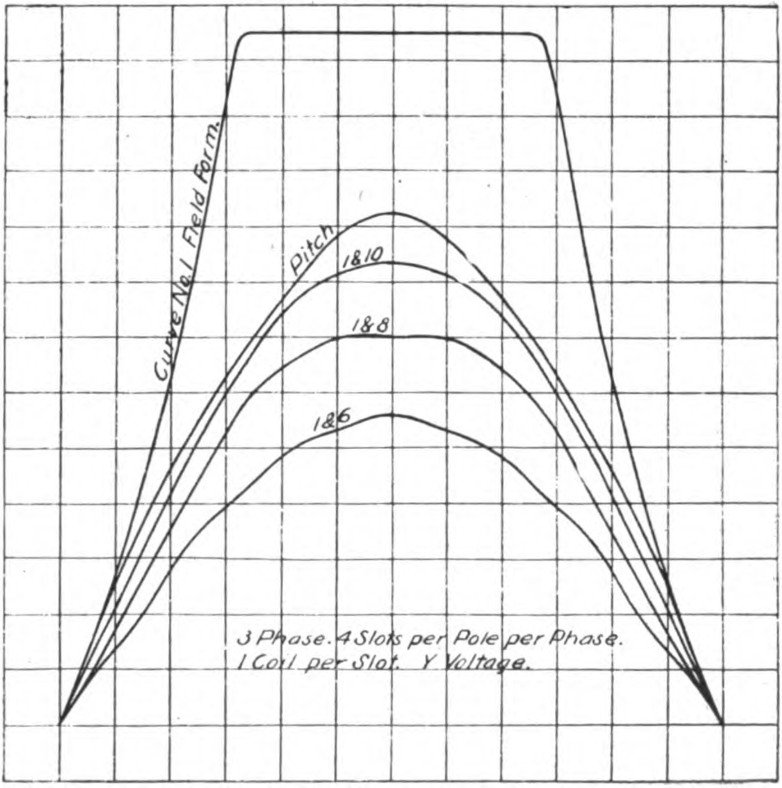

FIG. 1

induced in the winding, and, consequently, losses will arise. A one-coil-per-slot winding with the same chording will have far less influence upon the local currents flowing, as in this case the sides of the coils opposing each other do not lie in the same slots. Chording the two-coil-per-slot delta-connected winding down to 120 electrical degrees, cuts out the part of the self-induction due to slot and tooth-tip leakage so far as the internal circulating currents are concerned, and thus the only reactance left to oppose these currents is that of the coil-ends. This is the worst condition for a delta-connected winding.

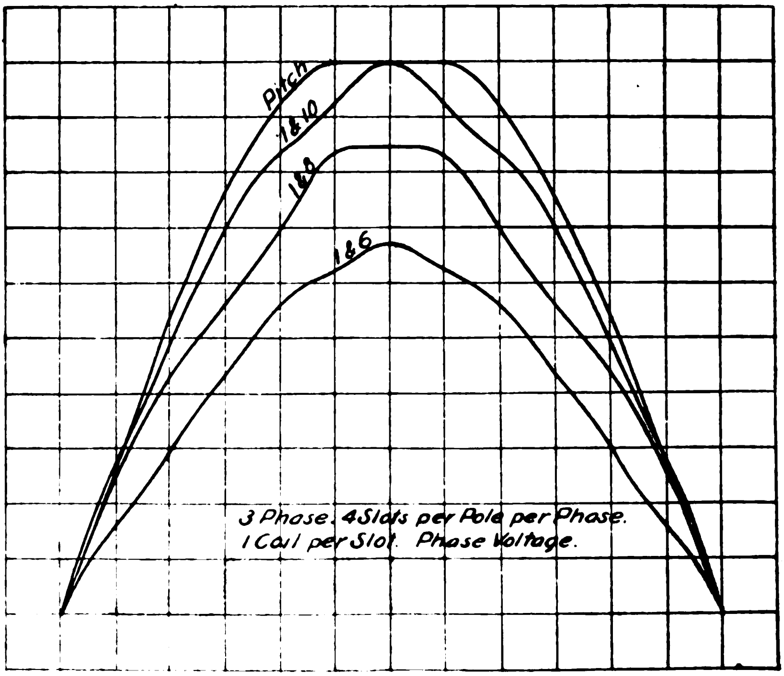

FIG. 2

It may be added that the chording of a two-coil-per-slot winding has also some influence upon the eddy-current losses set up in the armature conductors. As is well known, eddy-current losses are set up in the conductors, and, in cases of large copper section are considerable. The chording has the effect of bringing conductors belonging to different phases into the same slots, and thus the currents flowing in these conductors are not in phase, which again tends to reduce the eddy-current losses.

The effect of the chorded winding upon the wave-form. If the field form of the generator follows a sine wave, the chording of the armature winding will not change the form of the electromotive force wave; the wave-form will remain a sine wave. The more the field form departs from the true sine wave, the more will the influence of the chord show up in the shape of the wave-form. In the case of high-speed generators with a small number of poles, it is often, for mechanical reasons, not possible

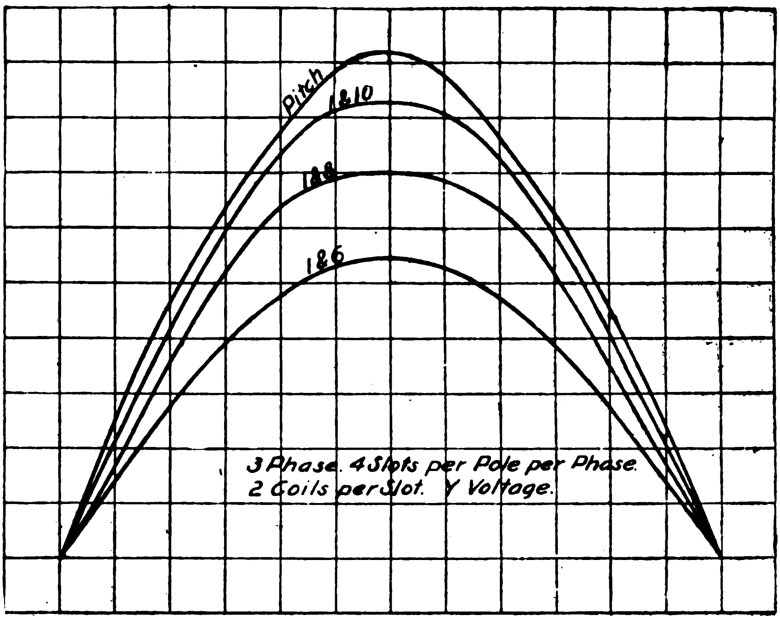

Fig. 3

to bevel the poles at all, or else it is not possible to bevel the poles in such a way as to give a smooth field form approximating a sine curve. At the same time a generator having a small number of poles will usually have a large number of slots per pole per phase, so that this will tend to smooth out the wave-form and make it approximately a sine wave.

Considering a generator having a cylindrical field construction, as in the case of a two-pole turbo-generator, the field form will be approximately as shown in Fig. 1, curve 1. For this field form the electromotive force wave-forms are plotted in

Fig. 1 for a three-phase Y-connected winding having four slots per pole per phase; the wave forms are plotted for pitch winding and for chord winding: 1 and 10, 1 and 8, and 1 and 6. It will be seen that the chord 1 and 10 improves the wave-form, but that 1 and 8, and 1 and 6, are distorted.

For the same winding and the same throws, the wave-forms of each leg are plotted in Fig. 2; these wave-forms would also be obtained when connecting the winding in delta. As is to be expected, these wave-forms are in all cases considerably more distorted than those shown in Fig. 1 and indicate the influence of the higher harmonics.

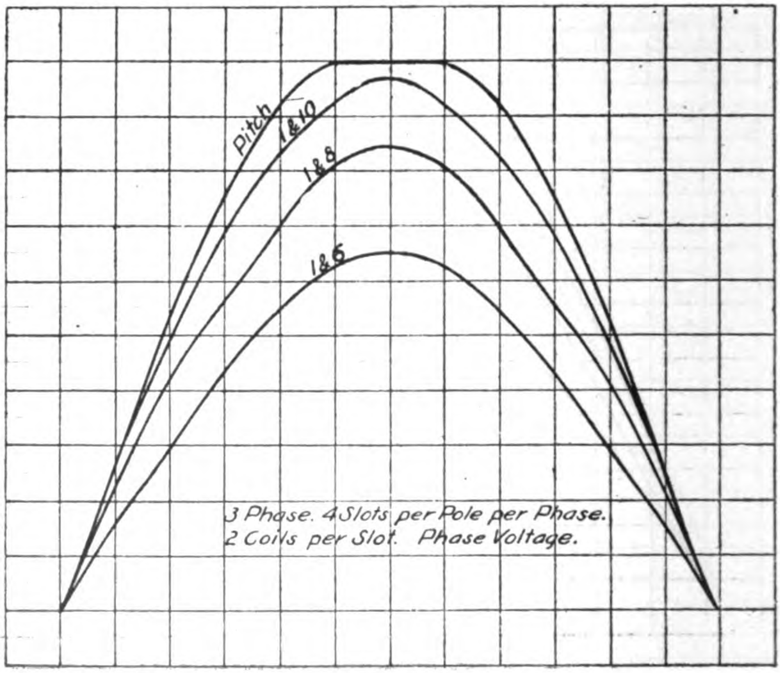

FIG. 4

Figs. 3 and 4 show the wave-forms for the same field forms and same number of slots per pole per phase when the winding is connected in Y and delta, but with two coils per slot. As the phases by these combinations are more distributed over the pole face, the wave-forms are less distorted than for the one-coil-per-slot winding; in the case of the Y connection the shape of the wave approximates as nearly a sine for the chord 1 and 6 as it does for the pitch winding. The wave-forms in Fig. 4, however, show evidence of higher harmonics of similar nature, but less pronounced than the one-coil-per-slot winding, Fig. 2.

As noted above, these wave-forms are plotted for a nearly rectangular field-form. The more the field-form approximates a sine curve, the less will the chord distort the shape of the wave. However, it is evident that the chord does have an influence upon the wave-form, and when chorded windings are used the wave-form should, therefore, be considered.

Conclusion. In determining the most efficient amount of chording, so many points are to be considered in each case that no general rules can be formulated. In cases where the chord is not made necessary solely for mechanical reasons, the most efficient chord will depend upon the number of poles, the ratio of pole-pitch to pole-length, the voltage, and the size of machine. These must be worked out in each individual case. The reasons then for chording the winding are:

1. To obtain the proper number of effective turns.
2. To enable form-wound coils to be used in generators of small bore and few poles.
3. To reduce the space occupied by the end-connections.
4. To improve ventilation.
5. To save copper and insulation.

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ELECTRICITY AS VIEWED BY THE INSURANCE ENGINEER; SHOULD THE A.I.E.E. INTEREST ITSELF IN FIRE PROTECTION?

BY C. M. GODDARD

If news had been received during the last six months of the total destruction of our fleet of battleships on its way to San Francisco, even without any loss of life, what a calamity it would have been considered, and how messages of sympathy would have poured in from all the governments in the world. The value of that fleet is probably less than $125,000,000; the property loss by the conflagration in the city of San Francisco, toward which that fleet was headed, of $350,000,000 by one fire, brought similar messages because it was an unusual occurrence.

The property loss by fire [in the U. S.] for the year 1907 was $180,000,000; the average annual loss for the last 32 years was $134,000,000; the national debt at its highest point was $2,845,000,000, or a little over two and three quarters billions; the insurance companies have paid $2,500,000,000 in losses since 1860; the total property loss by fire has been $4,250,000,000 since 1875.

There are approximately three hundred insurance companies doing business in this country, one thousand companies, or more than three times the present number, have failed or been retired since 1850. The three hundred companies have risks outstanding of over $30,000,000,000.

The annual number of fires in American cities averages 40 for each 10,000 of population as compared with 8 for each 10,000 population in European cities. The annual per capita loss in Austria, Denmark, France, Germany, Italy, and Switzerland varies from 12 cents in Italy to 49 cents in Germany, with an average of 33 cents as compared with $2.47 in the United States.

There is no question but that 50% of our fires are due to what we technically call "faults of management"; this includes all sorts of easily avoidable conditions that are likely to cause or aggravate fire hazard, a more common word would be "carelessness".

Just after the Collinwood School tragedy, a prominent metropolitan newspaper printed the following editorial on this unnecessary loss of life:

> A spasm of horrified emotion has passed over the country as a consequence of the deaths of a crowd of children in the fire which destroyed the Collinwood School at Cleveland. The horror is natural. It is a credit to the country. But the fire and its results were the natural effects of a succession of causes which discredit the country because they are characteristic of the country. The horror and the sympathy are human: they are common to all civilized communities; the recklessness which caused the unspeakable disaster is American. It has no counterpart elsewhere.
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> The city authorities, the school authorities, all were negligent. Behind their negligence stands the great, gaping negligence of the public, the same negligence that causes annually in the United States more accidental deaths and injuries than three great wars.
>
> There is terrific loss of life and limb in this country from preventable causes. No other land shows anything like it, or anything approaching it. This is not because of the vastness of our population, but because of its carelessness. We are the most careless people on earth. We permit a looseness of conditions, a recklessness of method, or a method of recklessness which would not be tolerated in Great Britain or Germany or France. This laxity runs on our railroads, pervades our coal mines, meanders in our mills, asserts itself in the slovenliness of our cities and our vacant lots and is traced directly to our homes along the icy sidewalks to our front doors and the doors of our churches and public institutions. The average American cares no more about the conditions outside the walls of his home than he cares about the conditions on the most distant planet. We are indifferent and unashamed. The spasms of public horror are soon over and forgotten. They accomplish nothing.

This arraignment of the American people applies with equal force to our fire loss and ought to bring the blush of shame to every public spirited citizen.

You are familiar with the idea embraced in the first part of the title of this paper, "Electricity as viewed by the Insurance Engineer", but do not the foregoing facts and figures warrant the second part of that title and demand not only from the electrical engineer but also from all classes of business men a careful and thoughtful consideration of the subject of fire protection and fire prevention? Should not every member of this Institute join hands with his fellow members of the National Fire Protection Association, and do his part to stop this appalling destruction of accumulated wealth?

" A penny saved is a penny earned " and while the insurance or fire protection engineer cannot create wealth as do the electrical industries, he can endeavor to lessen the unnecessary destruction of created wealth and thereby prove his right to exist. We cannot fairly throw the whole burden of this work on the insurance companies, their profit would be the same if they did nothing to reduce the fire loss and simply made it a matter of rates.

This is true of every public service corporation, but you men know that your best efforts are given all the time to reducing the cost of production, not solely to increase your profits, but because your great desire is to please your customer by giving him better service at a constantly decreasing cost and with a reasonably remunerative profit for yourselves. Do you not believe that the insurance companies are actuated by just as reasonable, honest, and business-like principles?

The market of the stock exchange is known to be the most sensitive barometer of the financial condition of the country. The prospect of poor crops, and therefore a poor year for the railroads, will cause a drop in prices long before the failure of the crop is assured. Are you surprised that the underwriting interests are equally sensitive, when you consider that the combined capital of the American stock companies in 1906 was $60,000,000 and the insurance at risk was $22,000,000,000, that the net surplus of all American and foreign companies doing business in the United States was $147,000,000 and the insurance at risk was $30,000,000,000? A fire in the congested value district of New York covering an area equalling that of the San Francisco conflagration would wipe out of existence nearly every insurance company doing business in that city. Do you not see, then, that it is but natural for such interests to " view with alarm " every newly introduced agent that may affect unfavorably the fire loss? Do you not realize that when the simple act of a cow kicking over a kerosene oil lamp can result in a Chicago conflagration, that the hazard of kerosene oil lamps is a very different proposition from what it would be if such a careless act on the part of that cow could only result in the destruction of the lamp, or, at most, of the building in which the lamp is located?

What must the fire protection engineer know? There is only one answer—he must know something about almost everything, he must be versed in the construction of buildings, in their equipment with fire protective and fire productive devices; he must know the hazards of all the different manufacturing and mercantile occupancies of such buildings. How can a man familiarize himself with every known business? He cannot. That is why he comes to you for advice. His work must be largely critical and that is the reason he is unpopular. He comes to you and asks you to create, and then to submit your creation to him to criticize; and he tells you this or that feature is likely to produce a fire, so he will have to charge an admission fee if you add your creation to his existing risk. This is unpleasant for you and for him too. He has his own troubles without seeking a quarrel with you.

Cannot you work together? Of course you can. Trust him, you are honest; and he is equally entitled to be considered honest. Talk it over, find out how your pet creation can be changed so as to remain just as attractive to you and become unobjectionable to him. It is your duty as a patriotic citizen of this country to do all in your power to reduce the fire loss. Work with him for that reason and because it will be for your advantage; your assistance will be welcomed, even if your prime motive is not love of the critic or of the insurance companies by whom he is employed.

It is my intention in this paper to direct your attention to the work of the fire protection engineer in a little different light from what you might expect from the title; but, you must remember that I am here now, not in my capacity as a member of this Institute but rather in that of a delegate from a sister engineering society, the National Fire Protection Association, a society of which this Institute is an active member. I am here to urge you to make that membership active, not only in name but also in fact, as far as you consistently can in connection with your other and regular professional duties.

I can probably never divorce myself in the minds of many of your members to whom I am personally known, from the insurance or underwriting interests, nor would I do so if I could; that is my life work and must claim my best efforts. In connection with that work, this Institute has, I am pleased to say, done able and efficient work, work that has been of great value to the underwriters, and, I firmly believe, of equal value to the great profession which you honor.

This is the first time that the National Fire Protection Association has been formally represented at an annual meeting of this Institute, and it seems to me that the time allotted to me in that capacity could not be better occupied than by endeavoring to show in a general way why there must be a close relation, either coöperative or antagonistic, between the electrical and the fire protection engineer. I could, of course, discuss some particular hazard or hazards of electricity as a fire producing agent, but if I can arouse in the membership of this Institute a sense of the duty they owe, not to the insurance companies but to mankind in general, so that each will give some thought and attention to electrical fire hazard problems, then we can trust to committees of conference to work out the details of each and all of the individual problems as they arise. Such work must always, in its results, be more or less of a compromise, often taking on a single point much more time than could be given here to the entire subject.

About fifteen years ago I suggested to some of the members of this Institute the desirability of active coöperation on the part of the Institute in the formulating of the underwriters' rules. But as this is, and should be a conservative body, it was not until 1896, in the National Conference, that the Institute itself took up this work, although many of its members had given valuable assistance from the outset.

You must admit that electricity may be a most serious fire hazard. The possibilities in that direction can hardly be estimated, and I believe that it was a most fortunate thing for the electrical interests that fire underwriters had begun to appreciate the necessity of fire protection before electricity was introduced for lighting and power, so that they immediately began to surround it with necessary and proper restrictions.

I think that no small part of the progress of your art has been due to the fact that in its early days, when the electrical engineer knew little about the fire hazard of electricity, the underwriter, knowing less but fearing much, appeared as an unwelcome but salutary obstructionist and at least caused the matter to be considered and investigated.

Some of the early fittings and methods of installation certainly would seem to justify any fears that the insurance interests may have entertained. I can remember when, back in the eighties, if the notches cut in floor timbers for gas pipes happened to be large enough, they were considered as a providentially prepared place for the wires, one on each side of the pipe. Now, through coöperation between the two parties in interest, how all this has changed; for I can stand here and tell you from the insurance interests that I believe any undue hazard from electricity has been and is being guarded against. You now give to us the safest illuminant and the safest source of power that we have. We welcome you in that you displace the open flame of gas or oil and the fire under the boiler, that you may by small power units do away with much shafting and the inherent liability of hot bearings. In order to retain this good opinion, however, we must continue our coöperation so that as your art progresses in giant strides, we may together keep pace with it in restrictions which shall not obstruct but safeguard its advance.

My great desire has been and is to foster and encourage this coöperation for our mutual benefit; our interests lie in the same direction, we must travel along together and put up with each others' faults whether we will or not. Shall we not walk as companions rather than enemies? Neither of us has a right to all the good things, nor deserves all the bad things; let us share the good things we each have and help each other with the bad things we must meet.

From the National Fire Protection Association, I bring you all a greeting and an assurance of a welcome if you will share their great work. From the underwriting interests, I also bring you greeting and assurance that we like you better as we know you better; but to the ordinary underwriter you represent a strange and unfamiliar creature, electricity, very difficult to comprehend. You do not know what electricity really is yourself, and how should we? It has served its time as a convenient substitute for our old friends, rats and matches and spontaneous combustion; it has proved its usefulness in many ways to us; it is rather erratic and sometimes inclined to stray from the path assigned to it, but on the whole it has improved so much, as it is reaching the age of maturity, that it is no longer of any particular use to us as a bugaboo to scare people with. Shall we not join hands and work together even more closely in the future than we have in the past?

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(*Subject to final revision for the Transactions*)

TESTS WITH ARCING GROUNDS AND CONNECTIONS

BY ERNST J. BERG

It has long been known that when an arcing ground occurs in a system, abnormal voltages and consequent failure of apparatus often result. This series of tests was started with the hope of being able to deduce some mathematical expression which would represent these phenomena with reasonable accuracy. The mathematical expression did not materialize, but in view of the importance of the subject, and believing that the results will prove of some interest and value, I give them in the following paper. The theoretical explanation might form the subject of a future paper.

In the tests power was supplied from a three-phase turbo-generator operated at 25 cycles and 11,000 volts. During the tests this generator also furnished power for railway and other purposes, so that the load, and therefore the wave-shape, was not the same throughout. Some endeavor was, however, made to find whether the outside load affected the readings, but the results were not conclusive and rather negative. It seemed, therefore, that at least in a general way the impressed, or rather the generated wave-shape of electromotive force was of little importance.

The current was carried to the experimental station through a three-conductor cable 4000 ft. long. The diameter of each conductor was 0.365 in. and the resistance 0.31 ohms. The capacity between conductors was 0.27 mf. and between each conductor and the other two and ground 0.45 mf. Two sets of 110-kw., single-phase, core-type transformers of similar type were used; one to reduce the voltage from 11,000 to 370, the other to raise the voltage from 370 to 33,000, the voltage used in the experiments. The arcing grounds were established on the high potential side of the transformers.

Fig. 1 gives the principal dimensions of the step-up transformers; that is, the transformers at the terminals of which the experiments were made.

The low-potential winding was made in four coils, each of 24 turns. These coils were placed nearest the core. The connections of the coils are shown in Fig. 2. The inside coil on one leg was connected to the outside coil on the other, and all coils were connected in series for 370 volts. The high-potential winding was in 18 coils, nine of which were on each core. The two outside coils, *A*, Fig. 3, had a tap brought out from the middle of the winding, the other coils, *B*, had no taps. The two *A* coils had each 426 turns, the *B* coils 482, making 8552 turns in all. The coils were connected as shown in Fig. 3.

In the paper one-half of the *A* coils is referred to as "the end coil," which, therefore, have 213 turns, or one-half of the turns of the *A* coils. The normal voltage between them is 2.49% of the primary voltage.

Terminals were brought out from the taps indicated. The exciting current was 3% of the full-load current, the core loss 1.2%. Primary and secondary resistances were each 1% The total reactance was 3.5%. The capacity between the primary and secondary winding was 0.003 mf., and the capacity between primary and secondary and ground was approximately the same. In all experiments the transformer cases were grounded.

The arcing connections between terminals or to ground were made by approaching a small wire to the terminal. Unless stated to the contrary, the arcing connection may be assumed to have practically no resistance. As will be seen in one of the experiments, substantially the same results were obtained when a resistance of several thousand ohms was inserted in the ground circuit.

The striking distances were taken by means of needle gaps in series with which were resistances of such a value as to limit the current to about 0.5 amperes. It was found that this resistance could be varied over a wide range without affecting the results, but that the actual contacts in the spark-gap circuit must be carefully made, since if an arc was established in any of the connections local oscillations were set up and too high striking distances resulted. The striking distances given represent the highest values obtained after a whole series of tests. These high values were, however, quite consistent so that tests repeated different days would check within a few per cent.

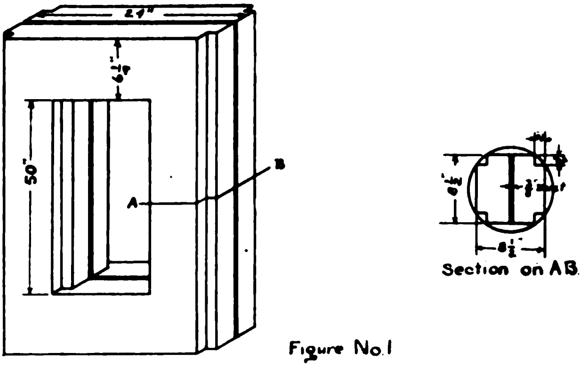


Figure No. 1

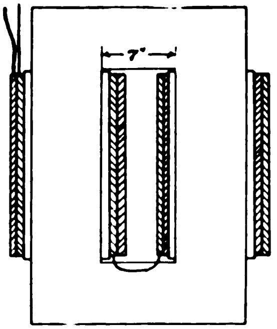


Figure No. 2.

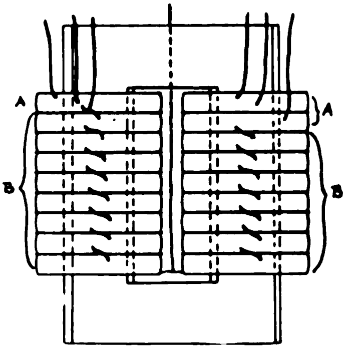
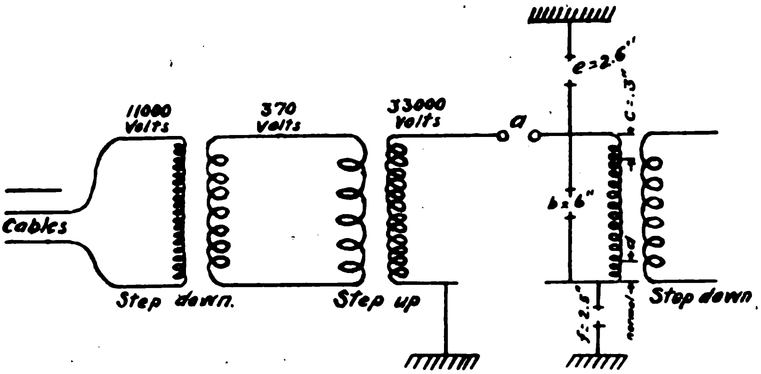


Figure No. 3

The normal striking distance between lines at 33,000 volts was 2 in. The striking distance across the first two taps—820 volts—was so low as to make the reading uncertain—it was less than 0.03 in.

In the first test which is shown diagrammatically in Fig. 4 one of the high-potential terminals of a 33,000-volt transformer was connected to one of the high-potential lines of another similar idle transformer through an arc. To introduce considerable capacity in the system, the other high potential line was grounded as was also the transformer iron. As the terminals *a* were brought within striking distance, a series of static sparks was established, which by their bluish-white color and snappy sound indicated a very high frequency.

Shunting the transformer was a spark gap, *b*, which at the time discharged over a 6-in. space; that is, three times the normal distance. A spark-gap, *c*, was placed across



Transformer diagram.

FIG. 4

the end coil, and this discharged over 0.3 in., or more than ten times the normal distance. It was found that gap *d* placed at the end of the winding did not show any abnormal voltage.

Needle gaps were also placed at *e* and *f*, between the end of the winding and ground, and these discharged over a distance of 2.5 in., showing that the winding was subjected to excessive voltage not only between turns, but also to ground.

In the second test, Fig. 5, the same general arrangement was used, but the ground connection of one of the lines of the step-up transformer was removed. Under this condition the spark at *a* was very faint, due to the slight charging current, and the voltages were very much reduced as seen in the figure, in which for convenience sake the striking distances are inserted directly instead of the spark gaps. These two experiments indicate what might take place when transformers are connected or disconnected by an air switch, or a switch which permits of some oscillations before the circuit is definitely made or opened.

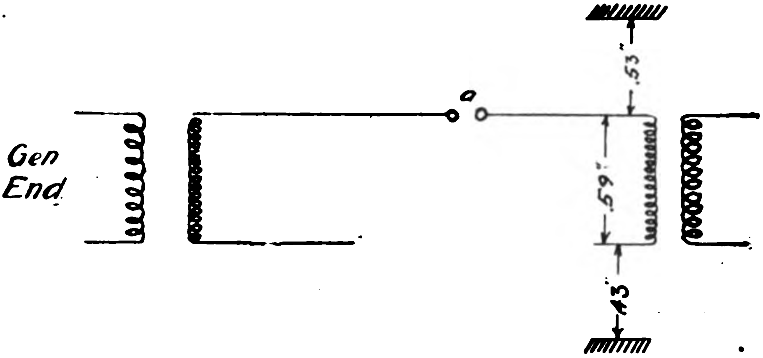


FIG. 5

In the third test an arcing ground was made at the terminal of the step-down transformer as shown in Fig. 6. With an arcing ground, the striking distance between the terminals and between one terminal and ground was 4.1 in. or more than double the normal value. Across the 2.5% tap nearest the

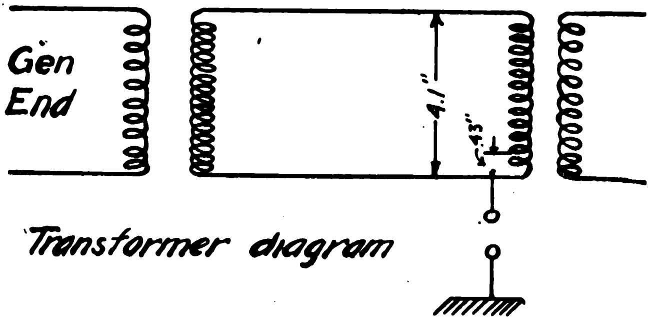


FIG. 6

arcing ground the striking distance was more than 15 times the normal, but no apparent abnormal voltage existed at the end coils on the ungrounded side of the transformers.

The fourth test was made with transformers connected three-phase. Three transformers with the primaries and secondaries connected delta were used to reduce the voltage from 11,000 to 370; three others, with the same connection, to raise the voltage from 370 to 33,000 volts. One of the high potential lines, or rather the junction of two transformer windings, since no transmission line existed, was grounded by an arc, as shown in Fig. 7.

The top diagrams indicate that delta-delta connection was used, and show the maximum striking distances across windings and across an end coil. The lower diagram is a scale drawing

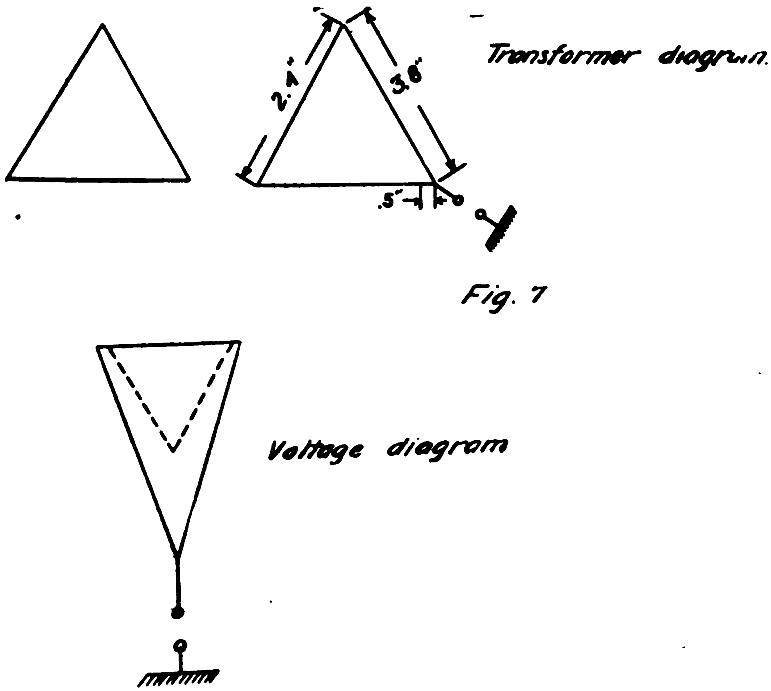


Fig. 7

to show the magnitude of the normal striking distance—in dotted lines—and those existing with the arcing ground.

It is interesting to note that the striking distance across the two transformers nearest the ground was 1.9 times the normal. The transformer opposite to ground was subjected to 1.2 times the normal voltage.

In the next two tests the step-down, as well as the step-up transformers, were connected open delta, or V. By referring to Figs. 8 and 9 it is seen that with this connection, particularly

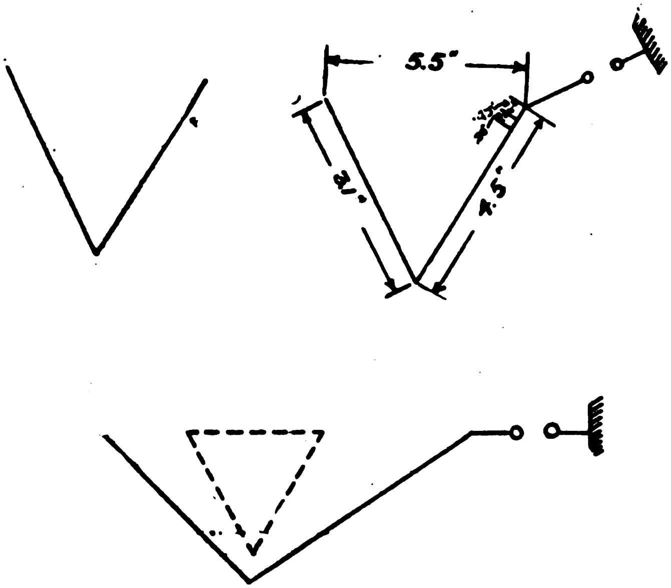


FIG. 8

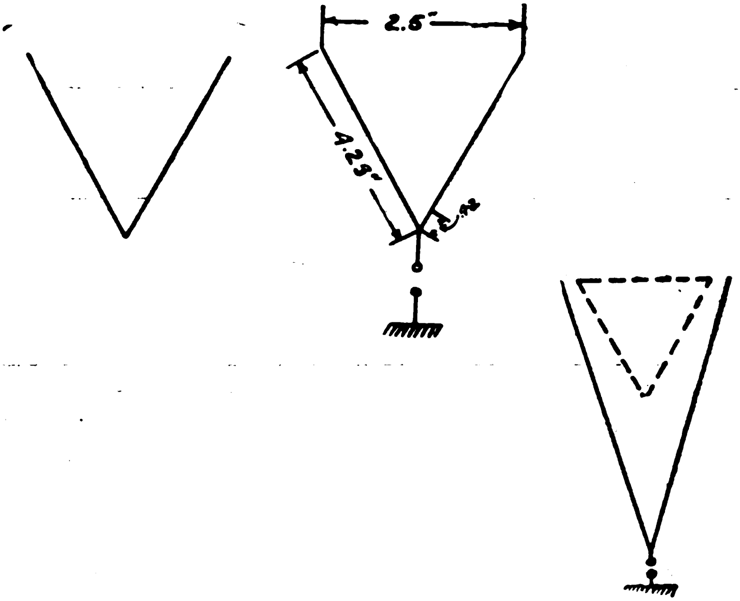


FIG. 9

when the arcing ground took place on one of the outside lines, the transformers were subjected to very high stresses. For instance, in the fifth experiment. Fig. 8, when an outside terminal was grounded, the striking distance between the other outside terminal and ground was 2.75 times the normal; across one of the transformers it was 2.2 times, and across the other 1.55 times the normal value. The striking distance across the first 2.5% tap was 0.45 in., or about 15 times the normal, across the next tap 0.3 in., or ten times the normal.

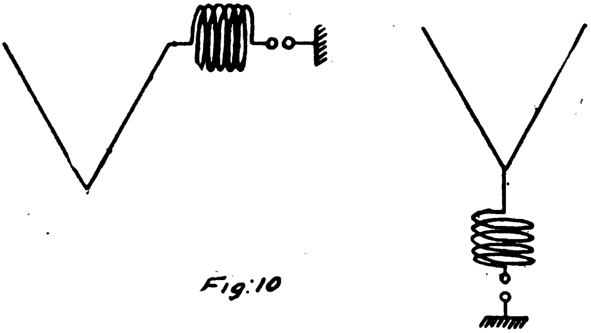
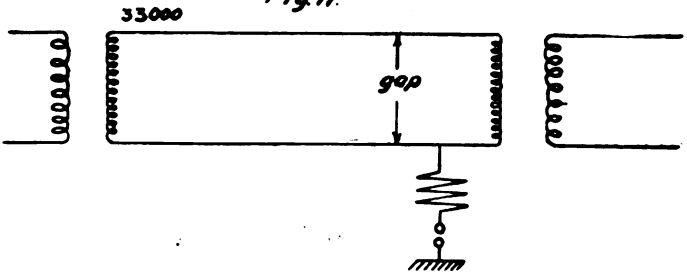


Fig: 10

In the sixth test, Fig. 9, the middle line was grounded and the striking distance across each transformer was 2.1 times the normal. In both experiments the striking distance across the end coil nearest the ground was from 15 to 20 times the noimal, but no abnormal voltage was detected at the end turns opposite the grounded side.

Fig. 11.



Resistance	0	16000	160000	340000	1×10⁶	2×10⁶
Gap length	3.6"	3.6"	3.5"	2.6"	2.5"	1.75"

In the seventh test a very wide range of inductance in the shape of air coils was inserted at the transformers, as shown in Fig. 10, and the ground made on the line side of the coils. These coils were of the same dimensions as the coils used in the transformer. It was found that the number of turns did not affect the results in any way that could be classified.

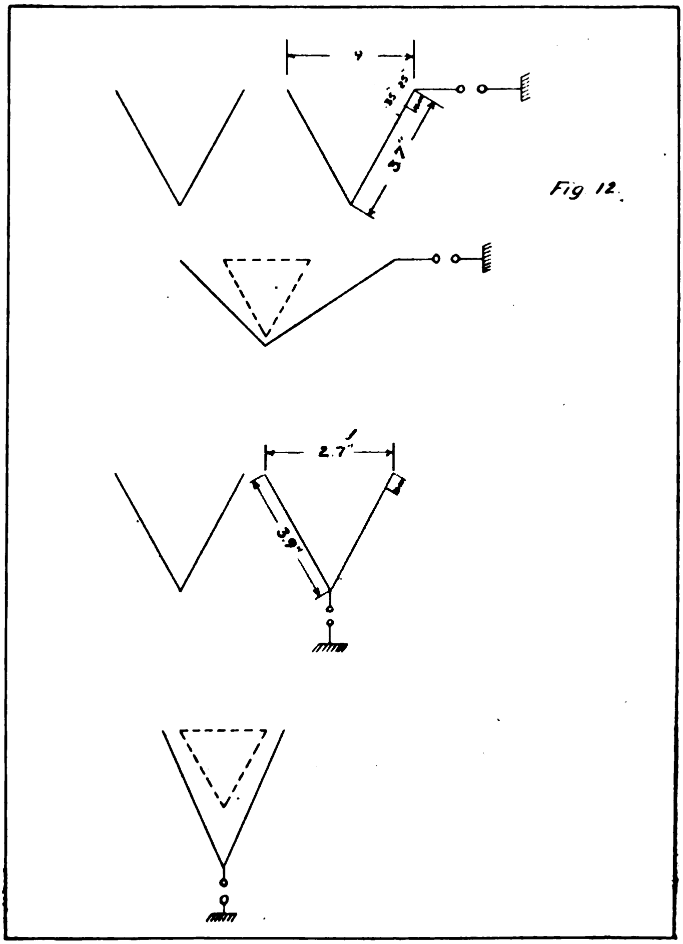


Fig 12.

At times a large reactance, say 20% of the transformer turns, would show lower striking distances, then suddenly perhaps the wave-shape slightly changed, or something else happened outside of the experiments, and the striking distances would be even greater than when no coils were used. The coils seemed to resonate with some of the higher harmonics; and since there is probably a large number of higher harmonics, each coil found one which suited the natural frequency of the transformer winding and the coil.

The eighth test recorded in Fig. 11, shows the effect of resistance in the circuit of the arcing ground. The diagram and the table explain themselves, and show in a general way that arcing grounds over insulators, through wood, etc., are practically as destructive as grounds without resistance.

Electrolytic cells in series with resistance

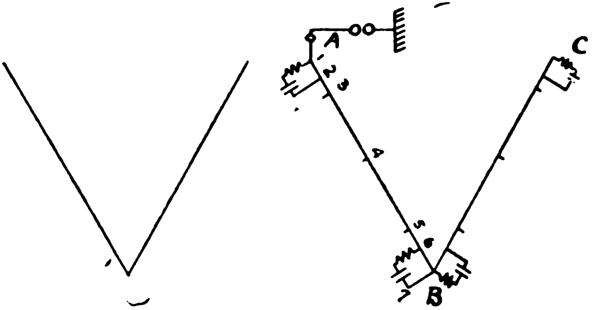


Fig. 13

Each cell consists of:-

175 Ohms.

Volts	AB	BC	AC	1-2	2-3	1-4	4-7
Gap	4 7/16	2 15/16	5 3/16	.045	.162	1 3/16	1 5/16

Various methods of relieving these strains, particularly the strains on the end turns, were tried.

For instance, in Fig. 12, which illustrates the open delta connection, the end coil was shunted by a resistance in series with a gap, the gap being so proportioned that a discharge would take place at abnormal voltage only. Various resistances were tried, but even the most favorable did not reduce the voltage entirely. By comparing Fig. 8 with Fig. 12, it is seen that the reduction in voltage across the first end turns was 50%, but the stress across the next coil was somewhat increased.

The voltages across the entire transformers were also decreased. It may be of interest to add here that this method of protection was quite effective at low voltages. This leads the writer to believe that with very high voltages when local oscillations of considerable energy are set up in the shunted circuit, this method will prove of relatively little value.

Electrolytic cells in series with resistance

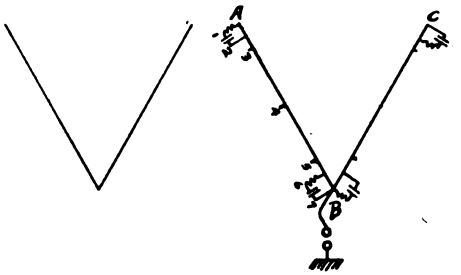


Fig. 14.

Arcing B

Each cell consists of ·

1000 Ohms.

Volts	AB	BC	AC	6-7	5-6	4-7	1-4
Gap	3 1/4	3 5/16	2 13/32	.135	.250	1 1/4	1 6/16

500 Ohms

Volts	AB	BC	AC	6-7	5-6	4-7	1-4
Gap	2 11/16	3 1/2	2 3/16	.170	.305	1 5/16	1 1/16

175 Ohms.

Volts	AB	BC	AC	6-7	5-6	4-7	1-4
Gap	2 13/16	3 9/16	2 3/8	.151	.365	1 3/8	1 3/16

Ordinary tin foil, mica and electrolytic condensers shunting the end turns were very effective in relieving the strain in the shunted coil, but transferred it to the next section.

Resistances in series with a few cells of electrolytic condensers caused some improvement as is seen by comparing Figs. 13 and 14 with Fig. 8.

Loading the transformers experimented with did not materially affect the results.

Finally, tests were made where one line was grounded permanently instead of through an arc, and it was found that no abnormal voltages existed, the striking distances being those corresponding to the impressed voltage. This suggests the advisability of making a permanent ground on any line which by some accident has become grounded, the permanent ground to be removed after the fault has been remedied.

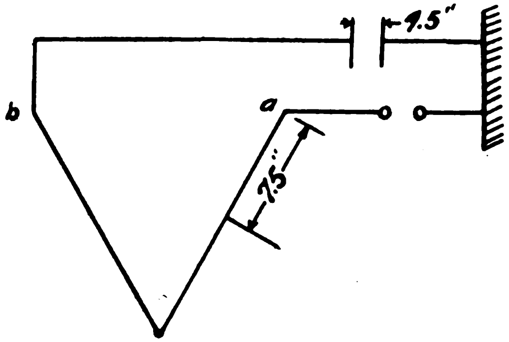


Fig. 15

Before closing it may be of interest to add an instance of the effect of an arcing short circuit which took place during one of the open-delta tests with the connections shown in the wiring diagram, Fig. 15.

Line *a* was grounded through an arc, line *b* connected to ground by an electrostatic voltmeter, having 4.5 in. distance between plates. As line *a* was grounded, an arc struck between the plates of the electrostatic voltmeter, resulting in a short-circuit on the transformers. At that time an arc struck from the terminal of line *a* to the terminal which was brought out from the middle of the winding, a distance of 7.5 in., or practically seven and a half times the normal striking distance. It is of course possible that the spark might have been still longer if the terminals had been further apart.

In conclusion it would seem as if with increasing line voltages it may be desirable to resort to some new methods of protecting the winding of transformers and other apparatus connected to the high-potential lines. One method might consist of a series of small electrolytic cells shunting the individual coils; by this arrangement these high-frequency surges would be transferred from each part of the tranformer to the lines. It seems unlikely that electrolytic cells shunting the lines but not connected to individual coils would entirely eliminate these internal disturbances, although with such cells there is no likelihood of the voltage across the entire transformer being materially increased.

Finally, it must be remembered that in these tests no high-potential transmission lines were used, and that, therefore, the results do not actually show what happens in a large system. From a few observations made in such systems the writer feels, however, that in general similar stresses result. Actual careful tests on such systems would prove of great value, bearing as they do on the choice of transformer connections.

A paper to be presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N.J., June 29—July 2, 1908.

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A STUDY OF MULTI-OFFICE AUTOMATIC SWITCHBOARD TELEPHONE SYSTEMS

BY W. LEE CAMPBELL

This paper treats of three principal topics:

1. The enormous economic waste which the wire, cable, and conduit equipment of a telephone system involves.
2. A recapitulation and discussion of reasons which make this waste necessary or expedient in manually operated systems.
3. How this waste can and should be greatly reduced in systems employing automatic switchboards.

In other words, as most automatic switchboard plants have been installed in conformity with practices which emanated from experience with manual switchboard systems, the writer will discuss some of the reasons for these practices and endeavor to show that they can profitably be ignored in plans for automatic systems. To accomplish this he has made a study of the principal factors in the first cost of plants of both types, together with certain factors in their operating expenses. Since many telephone engineers have possibly not had an opportunity to study these factors, and would be much interested in a comparison of them, the writer has so arranged his data that they will be of use, not only in the discussion of his theme, but also in a determination of the measure of success which automatic switchboards have attained in furnishing the speedier, more uniform, and more economical service expected of them by the men who labored so hard and faithfully to develop them, and by the pioneers who had the courage to be their early purchasers and operators.

The first cost of a telephone plant using switchboards of either type may be divided into three principal items:

1. Cost of the apparatus (both central office and subscriber's station).
2. Cost of the central office buildings and furnishings.
3. Cost of the wire, cable, and conduit plant.

In the third item of the first cost—the wire, cable, and conduit plant—we find the largest factor of the three. The writer will not attempt, however, to give any average figures on the amount of this item. It is a variable quantity, depending in each system, not only upon the number of lines in the plant, but also upon the character of the soil, upon the average length of line as controlled by the density of population, by the form of the city, by the relative location of the business center or centers, and by obstructions, such as rivers, lakes, etc., and upon other similar conditions. Under almost any circumstances this part of the system will cost more than the two other parts combined; not infrequently it represents two-thirds of the entire first cost of the system.

It will, therefore, probably tax the credulity of engineers, whose experience has been in connection with electric power and lighting, when the writer states that in the average telephone system containing one central office only, nine-tenths of the cable and wire plant is idle—not in use for transmitting conversations, even at the peak of the load; and, too, that on the average during 24 hours' service, 98% of the wires are not in use. Yet such is the fact. Indeed, from observations made in a large number of automatic plants during the busiest hour, it was found that in offices of from 8,000 to 10,000 lines, handling a comparatively heavy traffic, the maximum number of conversations taking place at one time was equal to slightly less than 4% of the number of lines in service. As each conversation represents two lines, this would indicate a maximum of 8% of the lines engaged for conversation, operating and signaling at the peak of the load.

Excepting party-line service, which at best is but a partial remedy, there is only one method known to telephone engineers of to-day for materially reducing the great economic waste represented in the 90% of the costly cable, wire, and conduit equipment which is not in use even during the " rush hours ". This method is to divide up each plant so that instead of one large central office it will employ a number of smaller offices. Just how much saving can be effected in this way, depends upon the local conditions in each city; but it will be readily understood that if small central offices or stations should be distributed over a city at the centers of well selected districts, the telephones in each district being connected only to the local station, the subscribers' lines would be decidedly shorter and cheaper than when all run for many blocks to a large centrally located office. For interconnecting between the district stations, only trunk lines would be needed, and it is necessary to have only enough of these to handle the busy-hour traffic; that is, the trunk lines need to be but a small percentage of the number of wires which would be installed if each telephone should be directly connected to one large central office.

An arrangement resembling that just outlined is in use in large cities, where of necessity some division has been made in manual systems for the reason that it is physically impracticable to terminate all lines in one multiple switchboard; that is, within the reach of each operator. Many telephone engineers do not consider it good practice to connect over 10,000 lines to one manual board, and while several boards have been installed with an ultimate capacity of 18,000 lines, the parts are so small and comparatively delicate that it is probable that repairs and depreciation will be exceedingly large items.

The writer does not wish to convey the idea that in manual practice systems are not divided up to save wire and cable; for in a very large city covering a great area this must be done. For example, in Chicago there are 15 or 16 central offices averaging about 3000 lines each. But division of an office of less than 10,000 lines is generally regarded as undesirable and to be avoided wherever possible. It is, therefore, the general practice in smaller cities to carry all or the bulk of the business on one large board, smaller branch boards being installed under suffrance and only for urgent reasons. The writer hopes to demonstrate that while this antipathy toward dividing offices of 10,000 lines or less is reasonable in manual practice, it is not reasonable in automatic practice.

Taking up the study of the factors that govern the first cost of a common-battery system of either type, and considering them in the order in which they have been named, we find first, that the cost of the ordinary direct-line, flat-rate telephone at the subscriber's station is about the same ($7.25 each) in all sizes and conditions of modern common battery manual plants, and $12.50 each in automatic plants. The cost of a private branch switchboard at a subscriber's premises is not materially affected by the size, location, or type of the central office to which it is connected. This, therefore, will not be taken into consideration.

The cost of the central office equipment when all installed in one office depends upon the number of lines entering the office, and the number of connections demanded during the busy-hour of each day. No storage feature is possible in a telephone plant. The switchboard must be designed to take care of the peak of the load, no matter how exaggerated that peak may be.

For the purpose of this paper, the writer has drawn, as shown in Fig. 1, an arbitrary curve, *A*, from which will be taken all figures used on the number of calls made per line per day in plants of different sizes. While this curve is not an unreasonable one, for flat-rate lines, it does not purport to be an exact average. Curve *B* in Fig. 1 shows the growth in the average number of lines in service and in the average number of calls per line per day in the "Chicago district" of the Chicago Telephone Company during the series of years, from 1893 to 1906. The writer supposes that the comparatively small traffic from 1893 to 1897 is largely due to the business depression then existing, and to the fact that the telephone had not then been sufficiently advertised to make it such an important factor, as it now is, in our business and social intercourse.

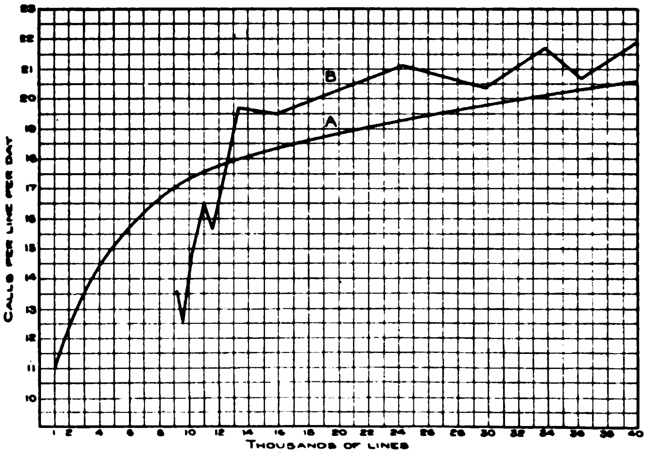

FIG. No. 1

CURVE "A" SHOWS ARBITRARY NUMBER OF CALLS PER LINE PER DAY, USED IN MAKING COMPARISONS

CURVE "B" SHOWS NUMBER OF CALLS PER LINE PER DAY IN CHICAGO DISTRICT FROM 1893 TO 1906.

W. L. CAMPBELL

It will also be taken for granted that the number of calls made during the busy hour of each day is one-eighth of the total day's business. Experience shows that this is an average ratio. The average busy-hour's work of an operator in the small manual plants is about 225 flat-rate connections; in the large manual plants about 250 flat-rate connections when no calls are trunked to other offices. In explanation of this difference in connections handled, it might be well to say that discipline is usually better in the larger offices, and consequently the operators do more work than in the smaller ones.

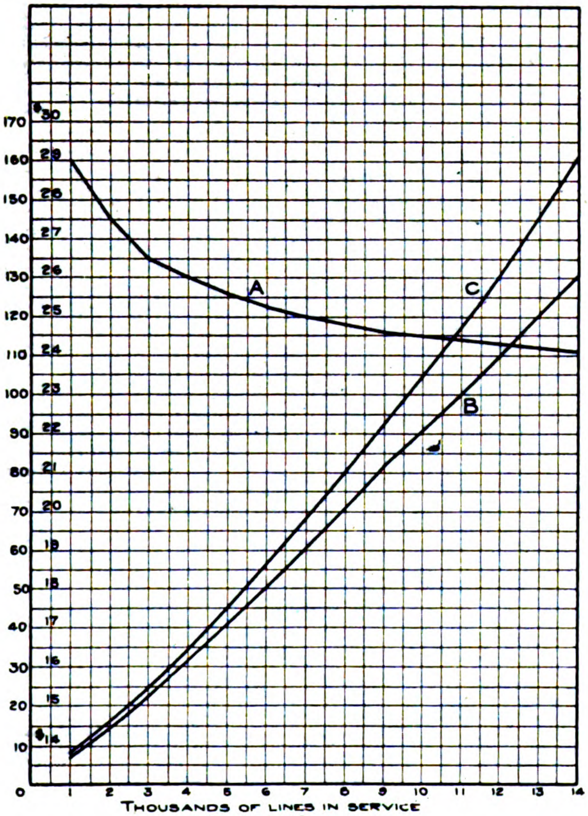

Fig. No. 2

Curve "A" Shows average number of lines in service per subscriber operators position.

Curve "B" Shows number of positions including hospital and long distance trunking positions.

Curve "C" Shows cost per line of all central office equipment except long distance equipment. (Manual offices)

W. L. Campbell.

With the foregoing points determined, curves *A* and *B*, Fig. 2, have been constructed. Curve *A* gives the number of flat-rate lines per operator's position, and *B* the number of operators' positions for manual switchboards equipped for from 1,000 to 14,000 lines, and for handling the number of calls per line per day indicated by curve *A*, Fig. 1. Curve *C* was then constructed, using the figures represented by curves *A* and *B* and the average prices at which a number of modern, well constructed, manual central office equipments using com-

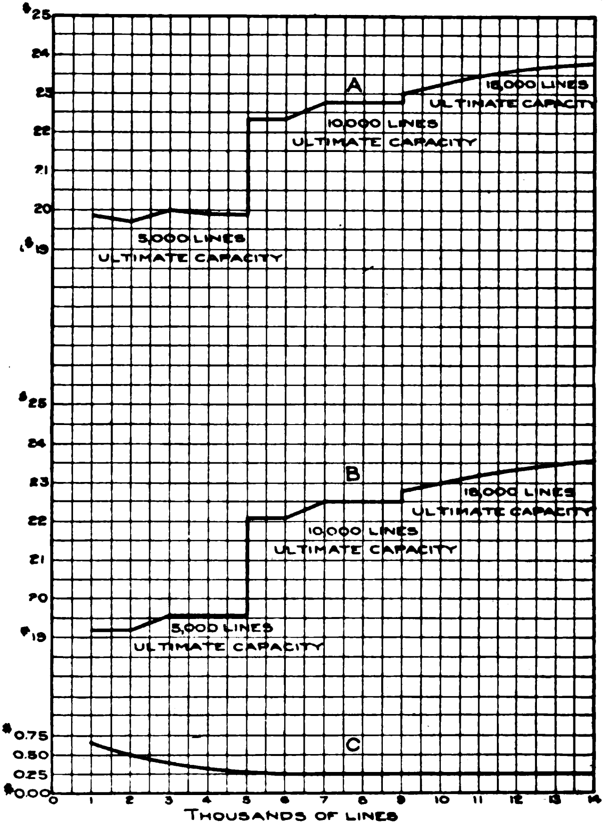

FIG. NO. 3

COST OF CENTRAL OFFICE EQUIPMENT FOR AUTOMATIC OFFICES. NO TRUNKING

CURVE "A" SHOWS TOTAL COST PER LINE OF CENTRAL OFFICE EQUIPMENT INCLUDING DESKS

CURVE "B" SHOWS TOTAL COST PER LINE OF CENTRAL OFFICE EQUIPMENT EXCEPT DESKS THE COST OF WHICH IS SHOWN BY CURVE "C"

CURVE "C" SHOWS COST PER LINE OF WIRE CHIEFS, TROUBLE CLERKS, INFORMATION CLERKS AND OFFICE SUPERINTENDENTS DESKS.

W.L. CAMPBELL.

mon-battery multiple switchboards have been sold and installed.

Curve *A* in Fig. 3 gives the cost installed of automatic central office equipment for offices of from 1,000 to 14,000 lines, designed to handle the number of calls per line per day as given by curve *A*, Fig. 1. The cost of central office equipment of either type includes cost of terminal racks, power plant, wire chief's, information clerk's and trouble clerk's desks; in short, all apparatus except a long-distance board and its accessories. In making up the figures on the cost of automatic equipment, the number of trunking switches necessary per hundred lines for handling the busy-hour traffic was taken from curve *A*, Fig. 4. This curve, which is the result of thousands of observations made in automatic offices, follows the empirical formula:

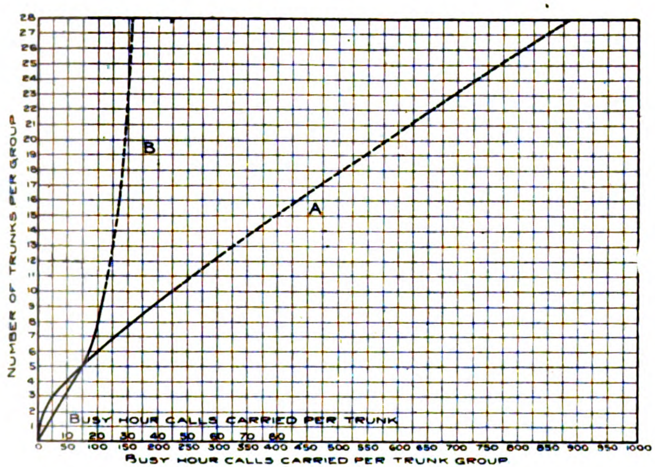

FIG NO. 4

CURVE A SHOWS RELATION BETWEEN NUMBER OF BUSY HOUR CALLS AND TRUNKS IN A GROUP FLAT RATE AUTOMATIC EXCHANGE CALLS AVERAGE HOLDING TIME 83 SECONDS

CURVE B SHOWS RELATION BETWEEN BUSY HOUR CALLS CARRIED PER TRUNK AND THE NUMBER OF TRUNKS IN THE GROUP AUTOMATIC SYSTEM FLAT RATE CALLS

$$\text{Trunks} = T\,C + 2.8\sqrt[3]{T\,C}$$

in which *T* represents the length in hours of the average connection and *C* represents the number of busy-hour calls.

For the benefit of those not familiar with automatic switchboards, the writer will state that each line terminates in what is generally called a line switch. These line switches are arranged and multiplied together in groups of 100 each. Connections between these groups are made by means of trunking switches called first selectors, second selectors, third selectors, and connectors. In a system having an ultimate capacity of 1000 lines, first selectors and connectors are the only trunking switches used. When the ultimate capacity is increased to 10,000 lines, second selectors are required also; and when the ultimate capacity is increased to 100,000 lines, third selectors are added. In a 100,000-line system, then, there is one first selector, one second selector, one third selector, and one connector for each trunk equipped.

A system with an ultimate capacity of 18,000 lines is made by installing a section of switchboard equipped for 8000 lines and arranged for an ultimate capacity of 10,000, and another section of switchboard equipped for the remaining 10,000 lines and using third-selector switches as if installed for an ultimate capacity of 100,000 lines. Such a combination does not involve any complications and makes the cost less than if the entire equipment were arranged for an ultimate capacity of 100,000 lines.

The cost of banks for ten selector switches of each type, and of ten connector switches per hundred lines, was included in all figures to allow margin for the practice, recently introduced into automatic plants, of moving selector and connector switches about from comparatively idle to busier sections in order to handle the busy-hour traffic with the least possible number of trunking switches. This practice is similar to that common in manual plants of apportioning the work among the operators' positions by means of an intermediate distributing frame.

In comparing these two first-cost curves (*C* in Fig. 2 and *A* in Fig. 3), it will be seen that the cost per line of manual equipment increases rapidly with the size of the office. This increase is principally due to the greater and greater number of multiple jacks which must be placed within each operator's reach, whereas, since the automatic is a trunking system, the cost per line is affected only by the slow growth in the number of trunks necessary to handle the busy-hour calls, and, at intervals, an increase in the ultimate capacity of the switchboard. The price of this equipment, therefore, rises more gradually and in the larger offices falls below that of the manual type.

For comparison only, the writer shows in curves *A* and *B*, Fig. 5, the respective costs of manual and automatic central office equipment as given by curve *C*, Fig. 2, and *A*, Fig. 3, plus the cost of one telephone per line.

Taking up the second item of first cost for single office systems, the writer would direct attention to Fig. 6 in which curves *A* and *B* give the square feet of floor space required on the average for automatic and manual central office equipments respectively. Curve *C* gives the cubic feet of space required for automatic equipment, and curve *D* gives the cubic feet of space required for manual equipment. In this same figure, curve *E* for automatic

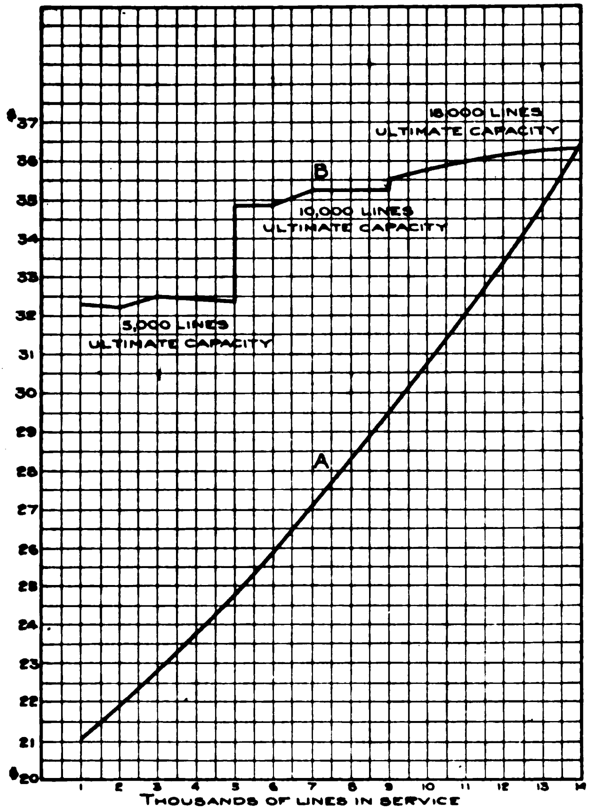

FIG. No. 5

COMPLETE COST OF CENTRAL OFFICE EQUIPMENT EXCEPT LONG DISTANCE BOARD PLUS COST OF ONE TELEPHONE PER LINE

CURVE "A" IS FOR MANUAL OFFICES.

CURVE "B" IS FOR AUTOMATIC OFFICES.

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equipment and curve *F* for manual equipment give the first cost of the necessary space in fire-proof buildings at an estimated rate of 19 cents per cubic foot for housing the automatic and manual equipments indicated. The cost of furnishings

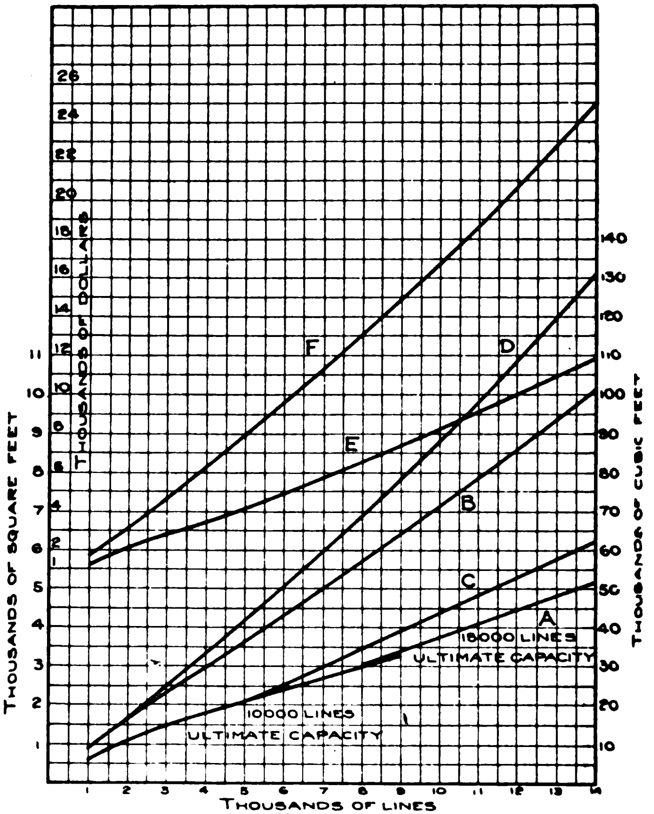

FIG. No. 6

CURVE A SHOWS SQUARE FEET OF FLOOR SPACE REQUIRED FOR AUTOMATIC CENTRAL OFFICE EQUIPMENT (NO TRUNKING)
CURVE B SHOWS FLOOR SPACE REQUIRED FOR MANUAL EQUIPMENT (NO TRUNKING)
CURVE C SHOWS CUBIC FEET OF SPACE REQUIRED FOR AUTOMATIC EQUIPMENT.
CURVE D SHOWS CUBIC FEET OF SPACE REQUIRED FOR MANUAL EQUIPMENT
CURVES E & F SHOW COST IN DOLLARS OF BUILDING SPACE REQUIRED FOR AUTOMATIC AND MANUAL EQUIPMENTS RESPECTIVELY FIRE PROOF BUILDINGS ESTIMATED COST 19 CENT PER CUBIC FOOT.

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and land, and cost of space used for executive offices, storage, etc., are not included, nor is the cost of space usually allowed for a growth of at least 20% or 25% in switchboards included. The figures do, however, include the cost of space for operators' rest rooms, hospital, dining room, kitchen, etc.

It will be noted that the cost of building space for automatic equipment is considerably less than that for manual equipment, and that for offices of over 5000 lines the automatic occupies about half the space required for the manual. No effort has been made to secure comparative figures on the cost of furnishings, but they are unquestionably more expensive in manual offices, since here recreation and rest rooms, restaurant, kitchen, etc., are commonly furnished and equipped for the use of the operators. In automatic offices the number of employees

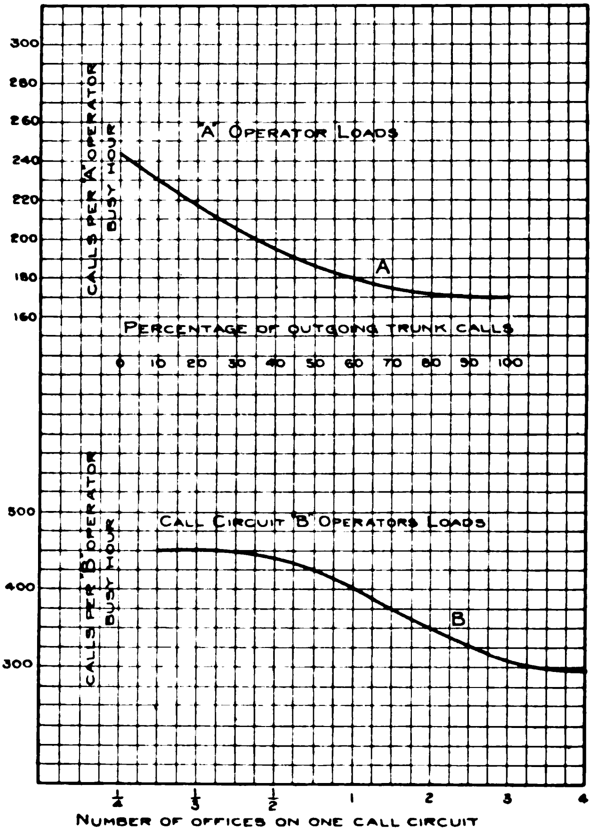

FIG. NO. 7
OPERATOR'S LOADS

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is comparatively small and the men are in the majority, consequently, it is not customary to make any elaborate provision for their comfort when off duty.

Having now shown what the average costs of the central office equipments and buildings would be in single office plants handling the traffic indicated by curve *A*, Fig. 1, it is next in order to see what effect dividing up a system so that it employs more than one office, has on these two items of first cost.

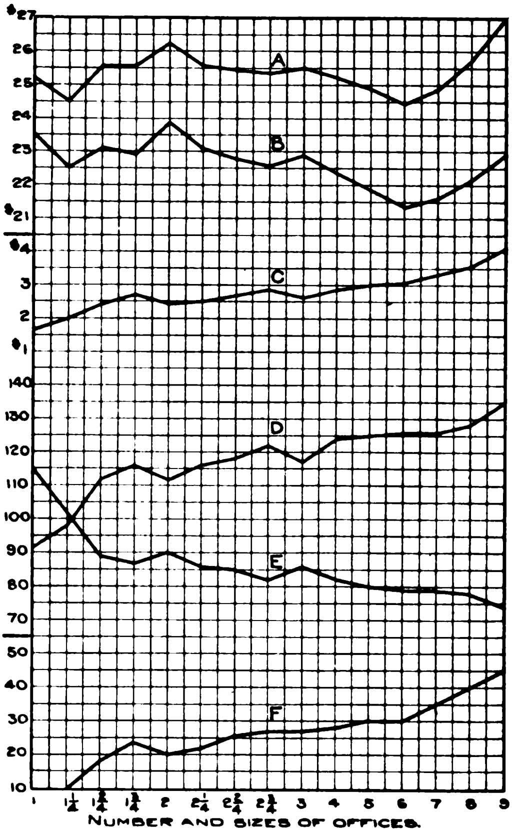

FIG. NO. 8

STUDY OF 10.000 LINE SYSTEM WITH VARIOUS NUMBERS AND SIZES OF MANUAL OFFICES
ESTIMATED 173.500 CALLS PER DAY ESTIMATED 21.687 CALLS DURING BUSY HOUR
CURVE "A" SHOWS COMBINED COSTS OF CURVES "B" AND "C"
CURVE "B" SHOWS COST PER LINE OF CENTRAL OFFICE EQUIPMENT
CURVE "C" SHOWS COST PER LINE OF BUILDING SPACE REQUIRED FOR CENTRAL OFFICE EQUIPMENT FIRE-PROOF BUILDINGS ESTIMATED COST 19 CENTS PER CUBIC FOOT
CURVE "D" SHOWS NUMBER OF "A" OPERATORS POSITIONS REQUIRED AT ALL OFFICES
CURVE "E" SHOWS THE AVERAGE NUMBER OF LINES SERVED BY EACH "A" OPERATOR'S POSITION
CURVE "F" SHOWS TOTAL NUMBER OF "B" OPERATOR'S POSITIONS
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In manual systems an operator's daily quota of connections is reduced when part of the calls which she handles must be trunked to other offices. This effect of trunking on the operator's work is indicated by curve *A*, Fig. 7, which gives the number of flat-rate busy-hour connections which one of the largest manual operating companies has found that an average "A" operator will make with various percentages of trunked calls. It is, therefore, necessary in a multi-office manual system to install and to provide space for more "A" operators' positions, as well as to install and provide space for "B" operators' positions and to provide increased space for rest rooms, etc.

As an illustration, in Fig. 8, curves *D*, *F*, and *E* show respectively the number of "A" operators' positions, the number of "B" operators' positions, and the average number of lines per "A" operator's position for a hypothetical 10,000-line system with different numbers and sizes of offices. The numerals along the bottom of the figure which indicate the various numbers and sizes of offices, have the following significance:

1¼	represents	1 office of 8000 lines
		1 office of 2000 lines
1²⁄₄	"	1 office of 6700 lines
		2 offices of 1650 lines each
1¾	"	1 office of 5725 lines
		3 offices of 1425 lines each
2	"	2 offices of 5000 lines each
2¼	"	2 offices of 4450 lines each
		1 office of 1100 lines
2²⁄₄	"	2 offices of 4000 lines each
		2 offices of 1000 lines each
2¾	represents	2 offices of 3650 lines each
		3 offices of 900 lines each
3	"	3 offices of 3333 lines each
4	"	4 offices of 2500 lines each
5	"	5 offices of 2000 lines each
6	"	6 offices of 1667 lines each
7	"	7 offices of 1429 lines each
8	"	8 offices of 1250 lines each
9	"	9 offices of 1111 lines each

It will be noted that the number of "A" and the number of "B" operators' positions grows quite rapidly as the number of offices is increased, while the number of lines per "A" operator's position diminishes.

In working out these curves the percentage of outgoing trunk calls from any office was calculated by the formula; trunking% = $100 \frac{A-B}{A}$ multiplied by 0.75; where A is the total number of lines in the system, B equals the number of lines in the office under consideration and 0.75 is a factor which experience indicates will allow under average conditions for the community of interest between the subscribers in an office district. Of course, in a study of a particular locality this factor should, if possible, be accurately determined; it may be as small as 0.4 or as large as 1.5.

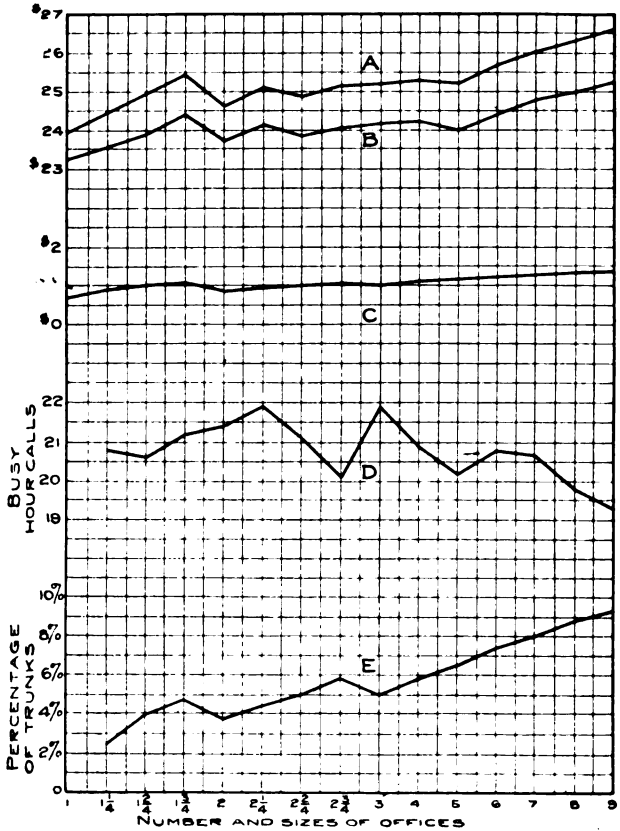

FIG. No.9

STUDY OF 10.000 LINE SYSTEM WITH VARIOUS NUMBERS AND SIZES OF AUTOMATIC OFFICES
ESTIMATED 173.500 CALLS PER DAY ESTIMATED 21,687 CALLS DURING BUSY HOUR
CURVE "A" SHOWS COMBINED COSTS OF CURVES "B" AND "C"
CURVE "B" SHOWS COST PER LINE OF CENTRAL OFFICE EQUIPMENT
CURVE "C" SHOWS COST PER LINE OF BUILDING SPACE REQUIRED FOR CENTRAL OFFICE EQUIPMENT
CURVE "D" SHOWS THE AVERAGE NUMBER OF BUSY HOUR CALLS CARRIED PER TRUNK LINE BETWEEN OFFICES
CURVE "E" SHOWS THE RATIO OF THE TOTAL NUMBER OF TRUNK LINES BETWEEN ALL OFFICES TO THE 10.000 SUBSCRIBER'S LINES ENTERING ALL THE OFFICES OF THE SYSTEM

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Curve *B*, Fig. 8, gives the approximate cost per line of the central office equipments installed as derived from the data used in curves *D*, *F*, and *E* previously mentioned. It will be noted that although more positions are necessary than in a single office, the cost of each position is reduced by a decrease in the line equipment and in the number of multiple jacks per position, so that there is not a great variation in the total switchboard cost. In the same Fig. 8, curve *C* shows the cost per line of the buildings for the various sizes and numbers of offices in the divided system. The cost of space required for executive offices, storage, etc., is not included in these figures, nor do they include the cost of land and furnishings. Curve *A* shows the combined cost per line of central office equipment and buildings. It will be noted that the greater cost of buildings is, to some extent, counterbalanced by a reduction in the cost of the equipment. The small increase would in any event be of little moment in comparison with the saving in the cost of the wire, cable, and conduit plant, which might be secured by plant division. It would, therefore, appear that we must look further for the cause of the objections to multi-office manual systems.

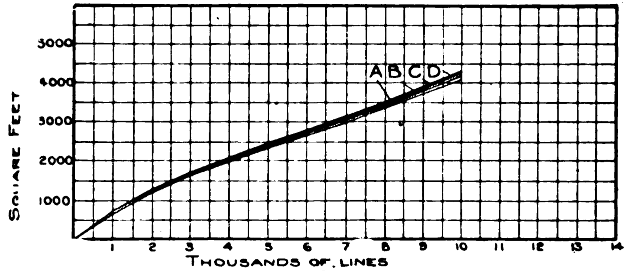

Fig. No. 10

Curve "A" Shows floor space required for automatic central office equipment of 100 000 lines ultimate capacity no incoming or outgoing trunk equipment.
Curve "B" Same as "A" except space added for equipment for 25% each of incoming and outgoing trunk calls.
Curve "C" Same as "A" except space added for equipment for 50% each of incoming and outgoing trunk calls.
Curve "D" Same as "A" except space added for equipment for 66% each of incoming and outgoing trunk calls

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Before discussing operating expenses, however, let us see what effect plant division has on the first cost of automatic central office apparatus and buildings. To illustrate the effect, the curves in Fig. 9 have been worked out, using the same 10,000-line system and the same numbers and sizes of offices employed in Fig. 8 for the manual system. The cost, installed, of central office equipment is somewhat increased by division, as will be noted by reference to curve *B*. The central office space required is also greater, as shown by curve *C*, Fig. 9, and by curves *A*, *B*, *C*, and *D*, Fig. 10. The slow increase in the combined cost of equipment and building as more offices are added is shown by

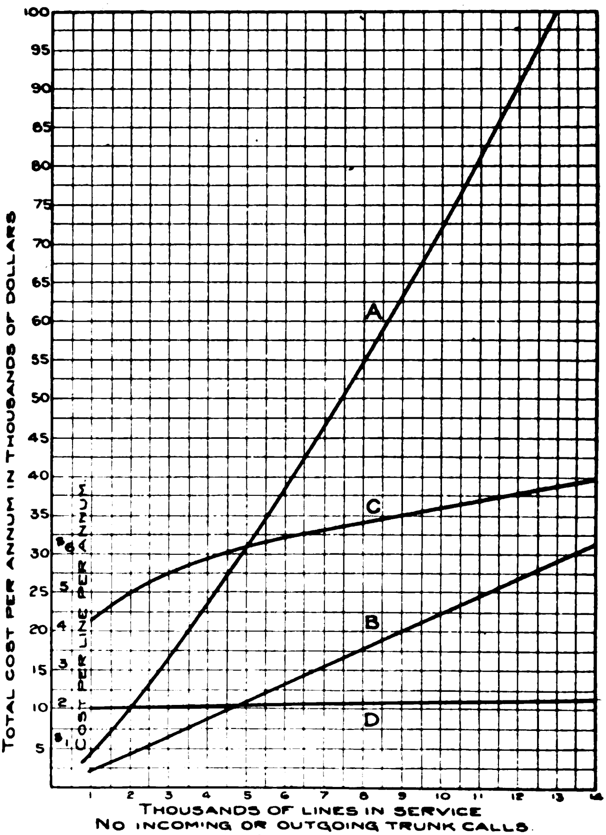

Fig. No. 11

Cost of labor for operating, repairing and maintaining all central office equipment except "Long Distance Board" includes also wire chief and assistants, trouble and information clerks

Curve "A" Gives total per annum for manual equipment
Curve "B" Gives total per annum for automatic equipment
Curve "C" Gives cost per line per annum for manual offices
Curve "D" Gives cost per line per annum for automatic offices

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curve *A*, Fig. 9. The increases are of small import in comparison with the saving in the underground and aerial construction secured by using a larger number of offices.

Taking up the subject of operating expenses, the writer would direct attention first to curves *A* and *C*, Fig. 11, which show average annual operating and maintenance labor cost for manual central offices of from 1000 to 14,000 lines, doing no trunking and handling the number of calls per line per day indicated by curve *A*, Fig. 1. Curves *B* and *D*, Fig. 11, show respectively the total annual cost and the annual cost per line of all central office labor for automatic offices of from 1000 to 14,000 lines. These figures are averages of the labor costs obtained from a considerable number of automatic switchboard operating companies.

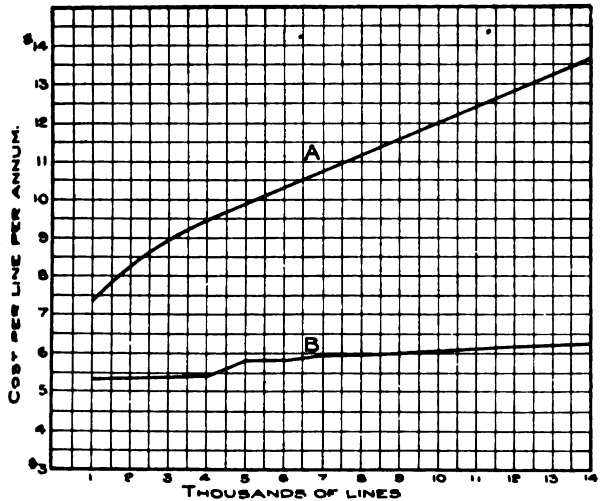

FIG. No. 12

CURVE "A" SHOWS COST PER LINE PER ANNUM FOR OPERATING MANUAL CENTRAL OFFICE AS SHOWN BY CURVE "C" FIG 11 PLUS COST OF POWER, LIGHTING AND INTEREST, DEPRECIATION, TAXES AND INSURANCE ON CENTRAL OFFICE EQUIPMENT AND ON CENTRAL OFFICE BUILDING

CURVE "B" SAME AS "A" BUT FOR AUTOMATIC EQUIPMENT (SEE CURVE "D" FIG 11)

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The writer would next direct attention to curves *A* and *B*, Fig. 12, which give the central office labor expense as shown in Fig. 11, plus the cost per line per annum of certain central office equipment and central office building charges that are materially affected by plant division. Curve *A* is for manual offices of from 1000 to 14,000 lines, no trunking, and curve *B* gives similar data for automatic offices. These figures include insurance, taxes, interest and depreciation on central office equipment and buildings, renewals for central office equipment, and the cost of lighting and power.

Insurance of the central office equipment in fire-proof buildings is taken at 1% per annum. Although several companies operating automatic apparatus have informed the writer that they secured a lower rate than that which they could get on manual equipment, it does not appear that the rating authorities have made any general rule which would assure a reduction. Since, however, much of the damage done to switchboards by fire is caused by blazes originating within the apparatus itself, and since the insurance companies exempt themselves from losses caused by such blazes, it would seem that fire losses would be smaller with automatic equipment than with manual. Manual switchboards are largely built of inflammable material and are incased in wooden cabinets. Also, if a blaze should start in one end of a manual board, there is little in the construction of the board to prevent it from sweeping through the entire length. Automatic switchboards are divided up into small separated sections so that a blaze in one would have very little opportunity to leap across to another. The apparatus itself is made up almost entirely of metal.

Taxes on both types of equipment are figured at the rate of 1.5% per annum; interest is figured at 6% per annum for both.

Depreciation on manual central office equipment is figured on an average life of 10 years. Of course, many parts of the switchboard must be replaced in less time: for example, cords in an average time of 1.5 years, plugs in 2 years, keyboard lamps 3 years, answering jacks 5 years, etc. These, however, are believed to be covered by including a 2% charge for maintenance materials and renewals. Depreciation on automatic equipment is calculated on a life of 12 years. Although no automatic plants, to the best of the writer's knowledge, have been in continuous service for this length of time, he has found that plants which have been in operation for 7 or 8 years show very little wear. While some such plants have been replaced by new ones, it has been because it was believed that better service and decreased operating costs, made possible by the new and improved equipment obtainable at the time the change was made, would pay for making it before the life of the original plant was exhausted. As an example, showing the effect of wear and tear on an automatic switchboard, there is in Fall River, Mass., an automatic plant which has been in operation for 7 years; at this plant the only appreciable wear is on the shaft wipers of the busier trunking switches. While these wipers could be renewed at a very modest expense, they will apparently last for some years yet. The wear on the equipment, which is individual to each subscriber's line, is hardly noticeable. In fact, an automatic switchboard has never been known to wear out, while manual switchboards are really worn out by the continued use of the parts by the operators. As the writer has already stated, such manual switchboard parts as cords, keyboard lamps, answering jacks, trunk jacks, etc., will need to be replaced at intervals during the life of the board. It is also found that the keyboards and plug shelves made of wood and sole leather become so worn from the continual contact of the operators fingers and the rubbing of the cords, and so battered by the constant pounding of the plugs, that they must be replaced in 6 or 7 years on a very busy board. In 10 years, or sometimes even less, the keys, multiple jacks, multiple cables, etc., are generally in such condition that it becomes necessary to replace the entire switchboard, regardless of whether it has become obsolete or not.

Ten to fifteen years ago telephone apparatus was being developed so very rapidly that the life of a board was not more than 5 or 6 years. At the end of that time the board would be so out-of-date that competition or a proper regard for service or for operating expenses would usually compel its replacement by a more modern one. That time ended in manual practice with the perfection and introduction of the common-battery multiple board. No radical improvements have since been made. Automatic switchboards have also reached a somewhat similar plane of development. For illustration, in the Fall River system installed in 1901, a subscriber makes a call by means of a dial, and secures service very similar to that in the most modern plant. Looking at the automatic switchboard itself, we find the so-called grouping system, the automatic selection of trunks, push-button ringing, and other essential features of the latest equipment. It is true that great improvements have been made in automatic equipment in very recent years, such as the introduction of common-battery service, party lines, line or individual switches, improved methods of manufacture, installation, etc., but these are all points which appeal to the manufacturer or to the operating company, while improvements in the general appearance of the telephones are about the only ones made in the last 7 or 8 years which are of much interest to the telephone users. Therefore, considering service only, and viewing the matter from the standpoint of the telephone subscriber, the writer believes it reasonable to conclude that there is little probability, in the near future, of a manual switchboard being rendered obsolete by a more improved manual board or of an automatic switchboard being put out of the arena by an automatic switchboard giving better service. He, therefore, has taken the life of a manual switchboard at the full amount that a consideration of wear and tear only will permit; and, in order to be perfectly conservative, has placed the life of an automatic board at but 2 years longer although there is no reason to suppose that it would not still be good for a number of years of service at the end of that time. The amount which must be set aside annually at 6% compound interest to equal 100% in 12 years is 6% of first cost. Therefore, this percentage is used in calculating depreciation on automatic central office equipment, while for manual equipment the depreciation charge is taken at 7.5%, which is the amount which must be set aside annually at 6% compound interest to equal first cost in 10 years.

Looking into the matter of maintenance material or renewals for automatic central office equipment, the writer has found from an investigation of a number of automatic plants that the renewals for the switchboard proper amount on the average to 0.2% per annum on the first cost of the central office equipment. The power plant, main distributing frame, and other parts of the central office equipment, increase the renewals item, however, and in order to cover everything it has been taken at 0.5% for automatic offices.

The cost of power per originating call handled is about twice as much for automatic switchboards as for most of the manual switchboards used by the "independent companies". The amount of current consumed is almost the same, 0.006 of an ampere-hour. Automatic plants generally use a battery of 46 volts, about twice the voltage of the usual manual battery, although in large plants where the lines are long, 40-volt batteries are sometimes employed in manual practice. The manual switchboards generally used by the Bell companies require considerably more current than those used by the independent companies. The amounts used by the independent boards have been taken in working out the curves in this paper. Taking the cost of power, transformed and delivered at the switchboards, at 15 cts. per kilowatt-hour gives a cost of $0.0216 per thousand local calls for manual offices and of $0.0432 per thousand local calls for automatic offices. The additional cost per thousand incoming trunk calls received at a manual office would be $0.0144. For automatic offices the additional cost for incoming trunk calls would be $0.004 per thousand, assuming that the number of calls trunked out from an office equals the number incoming.

The cost of lighting automatic central office equipment has been taken at $4.00 per thousand lines per month; and for manual offices the cost of lighting the operators' positions, the switchboard rooms, operators' retiring rooms, terminal room, desks, etc., has been taken at $2.00 per switchboard position per month.

The annual charges on the central office buildings have been taken at the same rates for the two systems; that is, insurance on fire-proof central office buildings has been figured at 0.5% per annum, interest at 6%, taxes at 1%, and depreciation and repairs at 2% per annum.

In order to illustrate the effect on the annual expenses, just discussed at length, caused by dividing a system up so that it employs a number of offices instead of one, the writer has constructed the curves in Fig. 13, which show what the expenses would be for the different numbers and sizes of offices in the hypothetical 10,000-line system used in Figs. 8 and 9. Referring to curve *A* in Fig. 13, it will be noted that the annual cost of central office labor for the nine-office arrangement of the manual system is 80% greater than for the single office arrangement.

It might be stated just here that the item of operators' hire is one which yearly grows to greater magnitude. One very large telephone operating company instructs its engineers engaged in development studies to estimate on operators salaries being at least 15% higher 15 years hence.

Curve *B*, Fig. 13, shows that the increase in the cost of labor plus the annual charges on equipment and buildings, weighs heavily against the division of manual systems. In fact, experience shows that where the ultimate number of subscribers that may be expected in an office district within fifteen years does not exceed the capacity of a single multiple board (about 10,000 lines) and there is no concentrated group of subscribers at a considerable distance from the best location for a single office, it is generally found that a one office system will be the most economical when manual equipment is used.

There are conditions under which it is profitable to divide manual 10,000 line plants; that is, there are conditions under which the saving in the annual charges on cable, wire and conduit, will more than offset the increase in central office expenses,

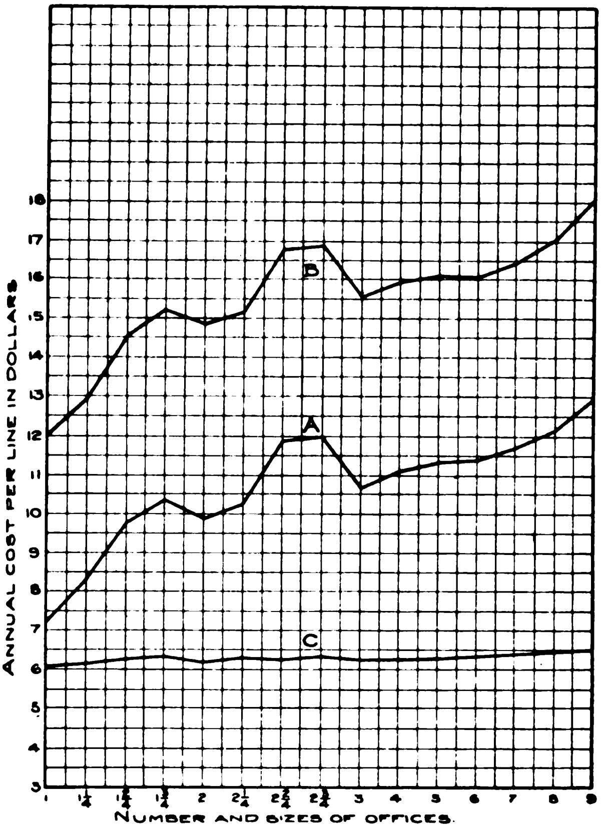

FIG. No. 13

CURVE "A" GIVES ANNUAL EXPENSE PER LINE OF ALL CENTRAL OFFICE LABOR FOR A 10,000 LINE MANUAL SYSTEM WITH DIFFERENT NUMBERS AND SIZES OF OFFICES THE SAME AS USED IN FIG 8

CURVE "B" SHOWS LABOR COST AS GIVEN BY CURVE "A" PLUS INTEREST, TAXES, DEPRECIATION MAINTENANCE AND INSURANCE ON MANUAL CENTRAL OFFICE EQUIPMENT AND ON CENTRAL OFFICE BUILDINGS, ALSO PLUS COST OF LIGHTING AND POWER.

CURVE "C" SHOWS FOR A 10,000 LINE AUTOMATIC SYSTEM (SEE FIG 9) THE SAME ITEMS AS THOSE GIVEN IN CURVE "B" FOR A LIKE MANUAL SYSTEM.

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if division is not carried too far. It is, of course, necessary to make a thorough engineering study of each apparently suitable location for a branch office, to determine whether or not any real economy would result; but since the annual charges on subscribers' lines less than two miles long using No. 22 gauge cable conductors average about $2.50 per mile, it will be seen that the saving in length of line will be less than the corresponding increase per line per annum in central office expenses (indicated by curve " B " in Fig. 13) except where the lines are comparatively long. Roughly speaking, an economical arrangement of the average divided manual system will include offices not much less than two miles apart.

Curve *C* in Fig, 13 shows that division of automatic systems may be profitably carried much further on account of the slow increase in central office expenses resulting from adding to the number of offices.

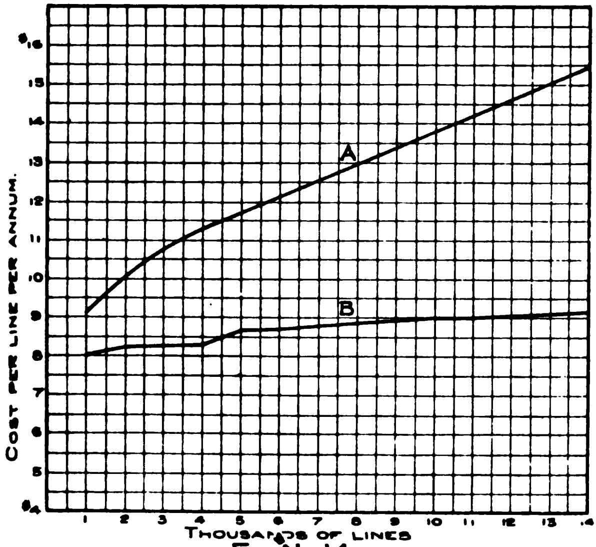

FIG. No. 14

CURVE "A" SHOWS COST PER LINE PER ANNUM OF MANUAL CENTRAL OFFICE AND CENTRAL OFFICE BUILDING EXPENSES (SEE CURVE "A" FIG 12) PLUS INTEREST, DEPRECIATION AND TAXES ON ONE TELEPHONE PER LINE AND PLUS COST OF CLEARING LINE AND TELEPHONE TROUBLE

CURVE "B" SHOWS COST PER LINE PER ANNUM OF AUTOMATIC CENTRAL OFFICE AND CENTRAL OFFICE BUILDING EXPENSES AS GIVEN BY CURVE "B" FIG 12 PLUS INTEREST DEPRECIATION TAXES AND CALLING DEVICE REPAIRS ON ONE TELEPHONE PER LINE AND PLUS COST OF CLEARING LINE AND TELEPHONE TROUBLE.

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The writer hopes that he will be pardoned if, before leaving the subject of operating expenses, he pauses to call attention to curves *A* and *B*, Fig. 14, which include the office expenses as given by curves *A* and *B*, Fig. 12, plus the annual cost per line of clearing line and telephone trouble, and plus the annual charges for interest, depreciation, and taxes on one telephone per line.

In calculating depreciation, the life of the telephones for both systems has been taken to be 10 years. It might appear unreasonable at first thought to believe that the more complicated automatic telephone has as long a life as the simpler manual instrument, but experience shows that the parts of a telephone which depreciate most rapidly are those which are handled by the user, knocked and rubbed against by passers-by and mischievous persons; also that the parts which must be kept highly finished, because they are exposed to view, are most quickly affected not only by human contact but by sunshine, dampness, etc. Consequently, since very little more of an automatic telephone than of a manual telephone is exposed, and since the calling device, which represents about 40% of the value of the instrument, is locked inside the case, where it is subject only to wear and tear of legitimate service, which it will successfully withstand for at least 15 years, the writer has concluded that automatic telephones could reasonably be considered to be longer lived on the average than manual telephones. He has, however, as already stated, placed the two on the same basis.

The cost of material for repairs and renewals on automatic telephones is a little greater than for the manual. It was found by a thorough investigation that the cost of new parts peculiar to the automatic telephones amounts to 0.14% per annum. This difference has, therefore, been noted in comparing maintenance costs of the two systems in Fig. 14.

The cost of labor for keeping telephones in order is included in the curves in Fig. 14 and for automatic telephones is also shown separately in Fig. 15. No insurance on the telephones is included.

Returning to the subject of plant division and its results, there is still another point to be considered, namely, the effect of plant division on service. An investigation of this reveals what is a very serious objection to a multi-office manual system; because slower service, more mistakes by the operators, and, what is most aggravating to a telephone subscriber, more premature disconnections during conversation, are the inevitable results of having connections handled by two operators instead of by one. The good will of the telephone user is something which cannot be lightly considered in these days of keen telephonic competition. Unpopular service is not only a serious handicap in a contest with a rival company; but it also retards growth, invites higher taxes and hostile legislation, and often results in a general clamor for the regulation and reduction of rates. On the other hand, a record of giving service which meets with the general approval of its subscribers is an asset of inestimable value to any telephone operating company, and, in fact, is the best reason for the company's existence. We find, therefore, telephone managers, who are chiefly concerned in pleasing the public, pretty solidly arrayed against having manual systems split up, except where the number of stations is so great or the area covered by the system so large that rates would be excessive if one central office only were used. In fact, "no divided systems," was one of the battle cries of the leaders of the independent telephone movement which has spread over the country so rapidly and so widely that its present magnitude baffles conception.

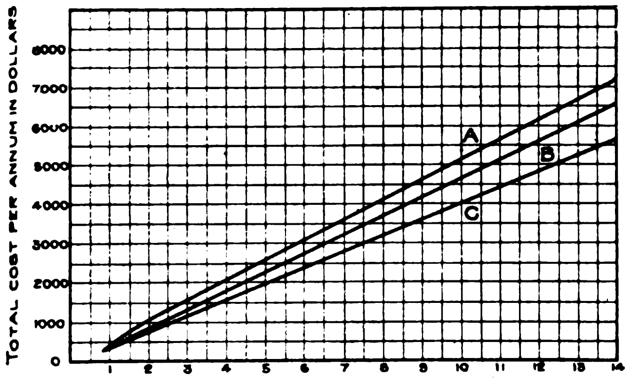


FIG. No. 15

COST OF LABOR FOR CLEARING TROUBLE IN AND MAINTAINING PHONES AND OF CLEARING LINE TROUBLES.

CURVE "A" SHOWS LABOR COST FOR CLEARING AUTOMATIC PHONE TROUBLE WITH RELATION TO TOTAL NUMBER OF PHONES IN SERVICE. (AUTO. C B. SYSTEM)

CURVE "B" SHOWS LABOR COST OF CLEARING LINE TROUBLE WITH RELATION TO THE NUMBER OF LINES IN SERVICE. (AUTOMATIC SYSTEM)

CURVE "C" SHOWS LABOR COST OF CLEARING LINE TROUBLE WITH RELATION TO THE NUMBER OF PHONES IN SERVICE. (AUTOMATIC SYSTEMS)

W L CAMPBELL

Increasing the number of offices in an automatic system does not appreciably affect the service. All calls are trunked anyhow, whether one office is used or many. Therefore, splitting up such a system does not add to the amount of trunking or in any way affect the speed and uniformity of service. The subscriber is not required to change his method of calling or to make more turns of his dial. No more automatic switches are necessary and a connection does not include any more switches in a divided system than in a single office plant. When the writer states that the service of a multi-office automatic system is on a par with that of a single office automatic system, he believes that he gives it the highest endorsement possible in the present state of the telephone art; for the companies operating automatic switchboards have demonstrated beyond question that they can give satisfactory service and furnish any special attention to which patrons of the girl-operated systems have been accustomed. Indeed, telephone users, who have had experience with both, almost universally prefer the automatic service to the manual. This fact is not only attested by all who have made an investigation, but has been publicly affirmed repeatedly in the reports of prominent public servants and engineers. For example, attention might be directed to the address delivered by Mr. Kempster B. Miller, before the International Electrical Congress at St. Louis, in 1904.

Not only has the writer not discovered any reasons which weigh materially against division of automatic systems, but he finds that the saving in the investment in cable, wire, and conduit would be even greater than in a manual system. First, because division may, as clearly shown, be carried much further without seriously affecting central office expenses, and secondly, because the number of trunk lines required for handling traffic between automatic offices is less than between similar manual offices. In other words, an automatic trunk will carry, on the average, more busy-hour calls than a manual trunk.

Curve *A*, Fig. 16, shows the call-carrying capacities which one of the largest manual telephone companies instructs its engineers to use in arriving at the number of trunks needed between proposed offices. As a rule, a manual trunk should not be expected to handle over 15 to 18 calls during the busy-hour even between rather large, well-managed offices; between small offices from 10 to 12 is all that can safely be depended upon. Reference, however, to curves *A* and B, Fig. 4, shows that between automatic offices a considerably higher trunk-carrying capacity is experienced. The largest number of trunks per group almost universally used in automatic systems is 10. Therefore, the curves in Fig. 4 are dotted above the line corresponding to 10 circuits per group. With groups of this size a minimum carrying capacity of 22.5 busy-hour calls per trunk is secured. This is a decided increase over the carrying capacity of manual trunks even where the latter are installed in groups of the greatest efficiency; that is, groups of about 73 circuits each. It would rarely, if ever, be possible to obtain such a large group if a manual plant were so divided that all offices were comparatively small, but in almost any multi-office system the majority of the trunks between offices can readily be placed in small groups of 10 trunks each. Consequently, in an automatic multi-office system maximum efficiency is secured on nearly all of the trunks. This is illustrated by curve *D*, Fig. 9, which gives the average minimum carrying capacity per trunk for each of the different arrangements of the hypothetical 10,000-line system. The average minimum number of busy-hour calls carried per trunk is, according to the curve, about 20.75, and the lowest figure is 19.3 for the nine office arrangement. Sup-

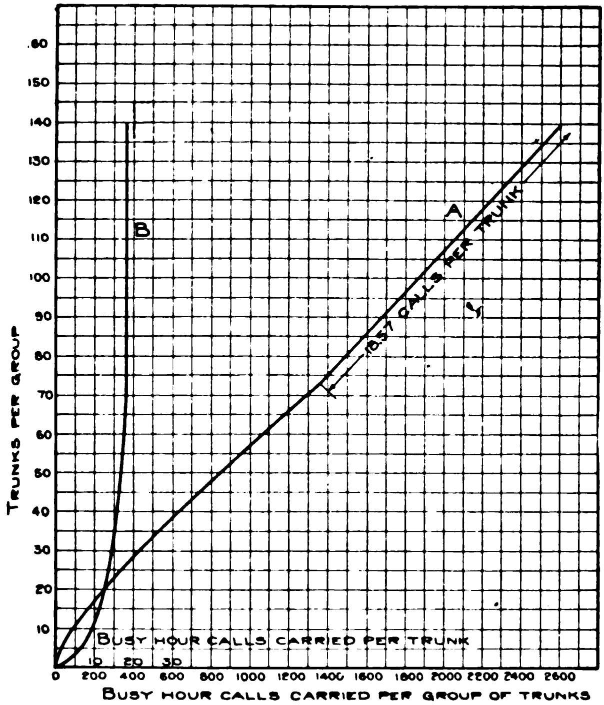


FIG. NO. 16

CURVE A SHOWS RELATION BETWEEN NUMBER OF FLAT RATE CALLS AND CIRCUITS IN THE GROUP. LOCAL "B" TRUNKS AVERAGE HOLDING TIME 2 MINUTES. MANUAL SYSTEM

CURVE "B" SHOWS RELATION BETWEEN THE NUMBER OF CIRCUITS PER GROUP. AND THE NUMBER OF BUSY HOUR CALLS CARRIED PER CIRCUIT

W. L. CAMPBELL

posing, for the moment, that it be practicable to use this nine-office arrangement in a 10,000-line manual system, the average number of busy-hour calls carried per trunk would be about 12.

The small number of trunks that will carry the traffic between automatic offices even in a thoroughly divided system is illustrated by curve *E*, Fig. 9, which shows the ratio on a percentage basis between the number of trunks and the number of subscribers' lines. With the largest number of offices considered this percentage is but 9.3.

One reason for the increased efficiency of automatic trunks is found in the shorter length of time per connection. In manual practice it has been found that each trunk is occupied on the average at least two minutes per connection, whereas automatic experience proves that during the busy-hour a trunk is not occupied over 83 seconds per average connection. A subscriber to automatic service answers his telephone quicker and generally does not hold the line so long for conversation as does a manual subscriber; also, the disconnection is made much quicker in the automatic system. This feature of the quicker disconnection is especially helpful during the busy hours when manual operators are most likely to be rushed and consequently slow about pulling down connections. The interval of time that elapses between release of a trunk by one automatic selector and seizure of it by another need be, and often is, but a fraction of a second. This, too, helps to increase the carrying capacity of the trunks.

The writer was much interested while studying the efficiency of the trunks of the two systems to note the difference between the number of connections existing at the busiest moment of the day in manual and automatic offices. For example, in the central office of a busy manufacturing city in Ohio a count was taken every day for a week in January of one year to ascertain the maximum number of connections "up" in the various operators' positions at intervals during the busy hours of each day. The results for the busiest day are shown in curve *A*, Fig. 17. A few months after these observations were made the equipment of this office was changed to the automatic type. In the following January, one year after the original data were secured, counts were made every day for one week of the number of connections "up" during the busy hours in the automatic switchboard. The results for the busiest day are shown in curve *B*, Fig. 17. It will be noted that the maximum percentage of connections counted at one time on the manual was 7 while on the automatic it was but 4.36. Similar observations were made on a number of automatic plants, and, as already stated earlier in this paper, it was found that in busy automatic offices of 8000 or 10,000 lines, the maximum number of connections counted at the busiest moment did not exceed 4%. In small offices of less than 1000 lines where erratic fluctuations of the traffic are more noticeable the maximum ran up to 4.7% in some instances.

A still higher trunk efficiency could often be secured in automatic systems if the trunk groups could be made larger than 10 lines each without impairing the speed at which idle trunks are selected. This is shown by the dotted portions of curves *A* and *B*, Fig. 4, which give the carrying capacity per group and per circuit for groups up to 28 circuits each. On account of the fact that in an automatic system where the number of offices is comparatively large, and each office is comparatively small, the trunks are generally divided into a large number of small groups, and it is doubtful if there would be anything gained by making the maximum size of a group of trunks between offices greater than 20 circuits. Indeed in such a system many of the groups would contain considerably less than 20 circuits each.

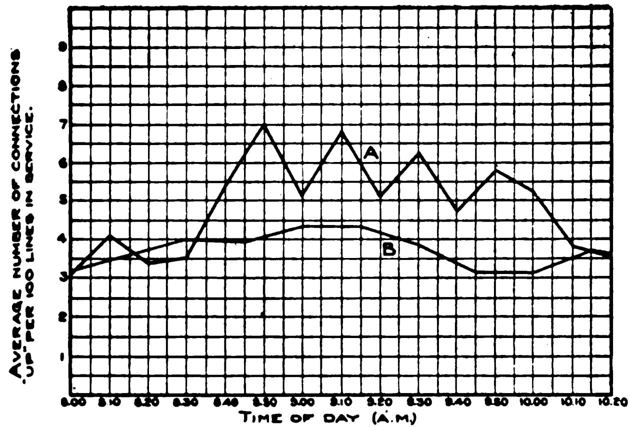


FIG. No. 17

CURVE "A" IS FOR A MANUAL OFFICE OF 2000 WORKING LINES AND 3088 TELEPHONES

CURVE "B" IS FOR THE SAME OFFICE WITH 2238 WORKING LINES AND 3112 TELEPHONES ONE YEAR LATER AND AFTER AUTOMATIC EQUIPMENT HAD BEEN INSTALLED.

The manufacturers of automatic apparatus have recognized the possibilities of larger groups and are now testing equipment designed to enable them to put more lines in each. Since such equipment has not come into general use, however, it will not be considered further in this paper.

In endeavoring to form some conception of the methods used for introducing trunking of calls on a large scale between automatic offices, it is well to understand the difference between two general types of office that are being used for this purpose.

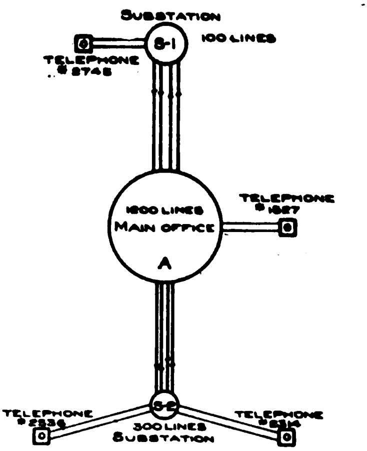


FIG. NO. 18

NUMBERS IN "A" OFFICE RUN FROM 1000 TO 2199
NUMBERS IN "S-2" OFFICE RUN FROM 2300 TO 2599
NUMBERS IN "S-1" OFFICE RUN FROM 2700 TO 2799

One is known as a " sub-station " or " district " office and the other as a " branch " office. The difference lies in that a sub-station contains line switches and connector switches but no apparatus for making local connections; that is, every originating call is trunked to a distant larger office containing the selector switches, whereas a branch office contains switches of all classes and completes within itself all local connections demanded. It will readily be seen, therefore, that a sub-station requires more outgoing and incoming trunks than a branch office.

For an illustration of a system using sub-stations attention is directed to Fig. 18, in which *A* represents a " main " office containing the equipment for 1200 lines. " A " contains also the first selector and second selector switches used by two substations *S*-1 and *S*-2. *S*-1 is represented as containing line switches and connector switches for 100 lines and *S*-2 is supposed to contain line switches and connector switches for 300 lines.

Calls would be handled as follows: suppose for example, a subscriber at telephone No. 2314, which is connected to substation *S*-2, to be calling No. 1527 connected to the main office *A*. The impulses sent over the circuit through the calling device of telephone No. 2314, would first operate a line switch at *S*-2, which would instantly extend the connection over an idle trunk to a first selector switch at *A*. This first selector switch would be operated by the impulses corresponding to the first digit " 1 " of the desired number, and, would extend the connection to a second selector, also located at *A*. This second selector would be operated by the impulses corresponding to the second digit 5 of the desired number and would extend the circuit to a connector switch in the " 1500 group " at *A*. This connector switch would be operated by the impulses corresponding to the last two digits 2 and 7 of the desired number and would complete the connection to line and telephone No. 1527. Suppose again No. 2314 to be calling No. 2745 connected to the other substation *S*-1. A line switch at *S*-2 would be operated first, then a first selector and a second selector at *A*. This second selector would extend the connection over a trunk to a connector switch located at *S*-1. This switch would be operated by the impulses corresponding to the last two digits of the desired number, and would complete the connection to line and telephone No. 2745.

Suppose again, No. 2314 to be calling No. 2536 connected to the same sub-station, *S*-2. In this case, a line switch at *S*-2 would, as before, extend the connection to a first selector switch at *A*. This switch would extend it to a second selector at *A*, which would extend it back over another trunk to a connector switch at *S*-2. This connector switch would complete the connection to line and telephone No. 2536. During such a conversation, therefore, two trunks would be occupied between the sub-station and the office through which it operates. This indicates that a sub-station is best adapted to a district where there is very little local telephonic intercourse, because every local connection occupies two trunks without any immediate benefit.

The sub-station is also especially adapted to a small isolated district where the expense of a constant local attendant would not be warranted, and, where it is, therefore, considered advisable to install the simplest apparatus obtainable, with arrangements for supervision from the main office to which the sub-station trunks are connected. Under almost any conceivable condition a sub-station will require more trunks than a branch office, for several reasons: first, all calls must be trunked; secondly, there is one group of outgoing and one group of incoming trunks for each 100 lines connected to the sub-station; thirdly, in order to provide thorough supervision from the main office, each outgoing trunk contains three wires instead of two.

It is, therefore, seen that in considering the advisability of installing a sub-station instead of a branch office, the increased expenditure for trunk installation and maintenance should be weighed against the saving in cost of supervision and attendance.

When the proposed office is to be a small one, and the trunks to it are to be secured by converting the line cable at present entering the new office district into a trunk cable, there is often no immediate advantage in economizing in the number of trunks. To such conditions a sub-station is well suited even if the trunks are long and consequently expensive. It would appear, however, that in the present state of the art such an auxiliary to a "main" office would rarely be warranted if it contained over 500 lines.

A sub-station may often be used to much better advantage as an auxiliary of a branch office; that is, a branch may be installed at the center of a comparatively large district so that all trunks going out from or coming into the district will terminate at the centrally located branch office, then shorter and more numerous trunks may be run from this office to sub-stations located about it. As an illustration of this plan please refer to Fig. 19 in which *A* represents an office of 5000 lines, *B* a branch office of 1500 lines, *S*-1 a sub-station of 100 lines, and *S*-2 another substation of 300 lines auxiliary to the branch office. Calls would be handled as follows: suppose, for example that a subscriber No. 8712 connected to sub-station *S*-2 called telephone No. 2134 connected to office *A*. As No. 8712 operated his calling device his line switch at *S*-2 would instantly operate and connect his telephone over an idle trunk to a first selector switch in branch office *B*. This first selector would be operated as the subscriber's calling device transmitted the first digit (2) of the number being called, and would extend the connection of the calling telephone over a trunk to a second selector switch at *A* office. The second digit (1) transmitted from the calling telephone would operate this second selector and extend the connection to a connector switch also located at *A*. This connector switch would be operated by the last two digits (3 and 4) of the number called, and would complete the connection to the line and telephone No. 2134. It might be of interest to note in passing that the current for the transmitter of the calling subscriber would be furnished from the battery located at *B* and the current to the called subscriber's transmitter from the battery located at *A*. If the call should proceed in the reverse direction, that is, if No. 2134 connected to *A* should call No. 8712 connected to *S*-2, then the operation of a line switch and a first selector switch at *A* would extend the connection over a trunk to a second selector at *B* which would in turn extend

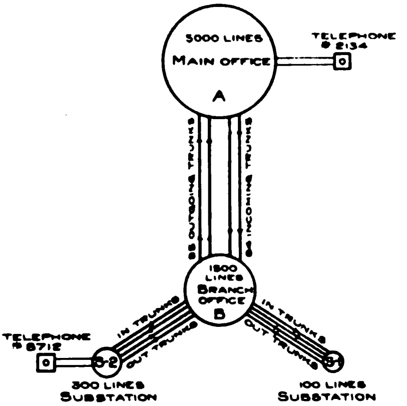


FIG. NO. 19

NUMBERS IN "A" OFFICE RUN FROM 1000 TO 5999
NUMBERS IN "B" OFFICE RUN FROM 7000 TO 8499
NUMBERS IN "S-1" OFFICE RUN FROM 8600 TO 8699
NUMBERS IN "S-2" OFFICE RUN FROM 8700 TO 8999

it to a connector switch at *S*-2. This connector switch would complete the connection to line and telephone No. 8712.

Supposing the number of calls made per line per day in this 6900 line system to be 16, and the number of busy hour calls to be one-eighth of the total, and that the "community-of-interest" can in all cases be taken care of by the factor 0.75, then the number of incoming trunks necessary to *B* from *A* would be 94, and the outgoing trunks to *A* from *B* would be 95, a total of 189. This number is 9.9% of the total of 1900 lines in the branch office district. The number of pairs of wires necessary for incoming and outgoing trunks, supervision, furnishing ringing current, charging substation battery and all other purposes between *B* and *S*-2 would be 78; that is, 26% of the 300 lines connected to the sub-station, and between *B* and *S*-1 would be 28 pairs, which equals 28% of the number of subscribers' lines connected to that substation.

In order to demonstrate the advantage that there may be in making the office *S*-2, for example, a sub-station instead of a "branch" office, the writer would direct attention to Fig. 20, in which is represented the same system as that in Fig. 19, except that the office *S*-2 is now considered to be a branch office of "B". *S*-2 would now contain first selector and second selector switches in addition to the line switches and connector switches. There would be no difference in the mode of operation so far as incoming calls to *S*-2 were concerned, but there would be a difference in the method for handling outgoing calls; also all local connections would be completed inside of the *S*-2 office. The principal difference in the outgoing connections would be that connections from *S*-2 to *A*, instead of passing through switches at *B* would be trunked direct from the first selectors at *S*-2 to second selector switches at *A*. The effect of this would be to increase the number of groups of trunks and consequently the number of circuits necessary between *A* and the *B* districts, so that with the particular case illustrated in Fig. 20 the total number of trunks between *A* and *B* would be increased by 15, while a reduction of only 12 circuits would be secured between *B* and *S*-2. It is, therefore, readily seen that if the distance from *A* to *B* is equal to, or greater than, the distance from *B* to *S*-2, that the branch office scheme in Fig. 20 would require more trunk mileage than the sub-station scheme in Fig. 19. The writer believes that this fairly illustrates the advantage that there may often be in using the sub-station as an auxiliary of a branch office.

As an illustration of how trunking of calls is done in a larger automatic system, Fig. 21 shows a rough skeleton of a 50,000-line system. This contains 5 main offices, *A*, *B*, *C*, *D*, and *E*, of which *A* has 8 branch offices and the other main offices each have 5 branch offices. Since this system has an ultimate capacity of 100,000 lines, all numbers would have five figures, but, as is customary, in place of the first figure a letter is used, which not only makes the number easier for the subscriber to remember, but also designates the office to which the number belongs. It is supposed that the main office *A* contains equipment for 2000 lines, the numbers of which run from 1000 to 2999; and that each of its branches contains equipment for 1000 lines, the numbers in *A*-3 running from 3000-3999, in *A*-4 running from 4000 to 4999, etc. Each of the other main offices is also supposed to contain equipment for 2000 lines, the numbers of which run from 1000 to 2999 in each. Of course, there is a letter prefix to each number corresponding to the office to which the number belongs. Each branch of the offices *B*, *C*, *D* and *E*

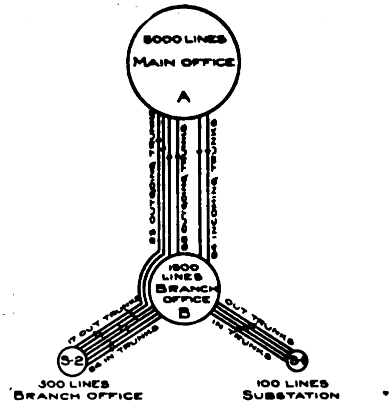
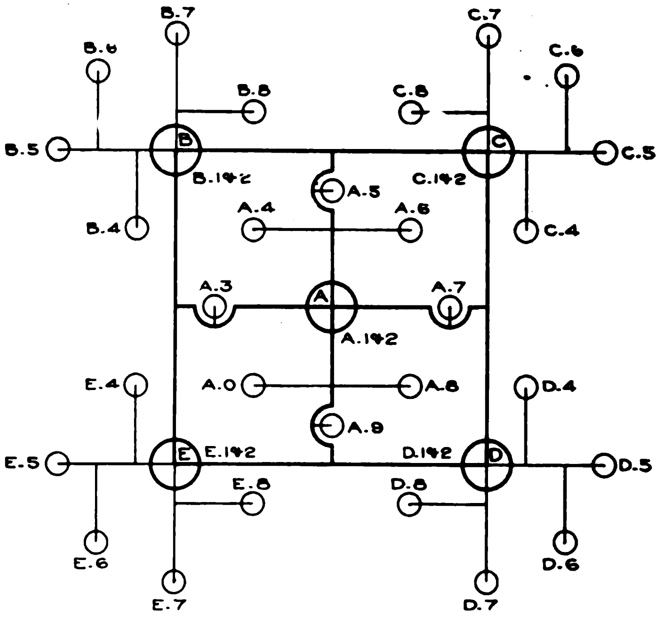


FIG. No.20

NUMBERS IN "A" OFFICE RUN FROM 1000 TO 5999
NUMBERS IN "B" OFFICE RUN FROM 7000 TO 8499
NUMBERS IN "S-1" OFFICE RUN FROM 8600 TO 8699
NUMBERS IN "S-2" OFFICE RUN FROM 8700 TO 8999

is supposed to contain 1000 lines. The numbers in *B*-4, for example, run from 4000 to 4999, those in *B*-5 run from 5000 to 5999, etc.

Connections in the system would be handled as follows:



SKELETON OF DIVIDED 50,000 LINE AUTOMATIC SYSTEM.
FIG. NO. 21

suppose a subscriber *E*-7234 connected to branch office *E*-7 called *A*-5124 connected to the branch office *A*-5. The first movement of the subscriber's calling device would operate his line switch and connect his line to an idle first selector in his own exchange, *E*-7; then when the calling device sent in a number of impulses corresponding to the No. *A*, his first selector would be operated and would pick out an idle trunk to a second selector in exchange *A*. The second set of impulses corresponding to the figure 5 sent in by the calling device would operate the second selector at *A* and extend the connection over an idle trunk to a third selector in the office *A*-5. The next set of impulses corresponding to the 1 of the desired number would operate a third selector at *A*-5, which would extend the connection to a connector switch in the proper "100 group" at *A*-5. This connector would be operated by the impulses corresponding to the last two digits of the desired number and would complete the connection to line and telephone *A*-5124.

It may be noted that on this call the connection to *A*-5 passes through the main exchange *A*. This would be true of every call incoming into the *A* district; that is, all trunks incoming into the district would terminate in second selectors in the *A* office. These second selectors would extend each incoming connection to a third selector located at the *A* main office, or at the branch corresponding to the thousands digit of the particular number being called. This concentration of the incoming circuits simplifies the trunking arrangement and also reduces considerably the number of trunks entering the district, because the number of groups of incoming trunks would be nine times as great if each of the nine offices received its calls, coming from outside the district, direct instead of having them come through the main distributing office *A*. It should be noted on the other hand that the outgoing call from *E*-7 does not operate any switch at its main office *E*. It would probably be preferable, however, to have the trunk pass through the cross connecting frame at *E*. In a similar manner all outgoing trunks from each of the branch offices of *E* district could be terminated on the distributing frame at *E*, and there be cross-connected to what might be called a "through trunk cable" to each of the other main offices. If a subscriber connected to any office in the *A* district should call a number connected to an office in *E* district the incoming trunk to *E* district would terminate in a second selector switch at main office *E*, and would be passed on by it to the desired branch office or thousand group. In the skeleton diagram no trunk cables are shown interconnecting the branch offices of a district; for instance, no interconnection is shown between E-6 and E-7. If desired such trunks could be put in, or the outgoing trunks from all the branch offices of *E* may, as already stated, be run to the main central office and there be cross connected on a distributing frame. This would in many cases be the most economical arrangement, because with division carried to the extent that it is in this diagram the number of trunks required between *E*-6 and *E*-7 would be comparatively small. A call from a subscriber at *E*-7 to a subscriber connected to *E*-6 would operate a line switch, first selector and second selector at *E*-7 and a third selector and connector at *E*-6 so that it is not necessary that the connection should pass through the main office *E*.

If a manual system should be divided up in the manner shown in Fig. 21, supposing for the moment that such a division would be practical with equipment of that type, then the branch office *E*-7, for instance, would have 32 different groups of outgoing trunks; that is, one group for each of the other offices in the system, and would have the same number of groups of incoming trunks. With the automatic branch office arrangement, *E*-7 has but 10 groups of outgoing trunks; that is, one group to each of the other district main offices and one group to each other " thousand section " in use in its own *E* district. *E*-7 would have but 5 groups of incoming trunks; that is, one group from each of the other offices in the *E* district. It is, seen, therefore, that by using the main offices at centers of comparatively large districts and then surrounding each main office with smaller branches, all subscribers lines may be made very short and the use of the " through " trunks between the main offices for interconnecting districts makes the trunking system comparatively simple.

It is probably unnecessary to add that in planning such a system as is represented by Fig. 21, a careful engineering study should be made for each branch office to determine whether the trunk mileage required would make a " branch " office or a " sub-station " the most economical arrangement.

One of the peculiarities of the telephone business, especially when there is competition, is that an operating company is compelled to take on the new business offered. It must keep up with its rival or drop out of the race. A user of electric light doesn't care how many other customers are connected to the same plant that he is, but a telephone user is, of course, very much attracted by the larger of two lists of subscribers. Unfortunately a one-office plant is somewhat like a water or gas plant, in that new customers cannot be constantly added by simply connecting their service pipes to the mains originally installed. Some day a point is reached when the mains are supplying all the flow of which they are capable and it is necessary to go back to headquarters, dig up the streets anew, and put in more mains or larger ones. So in a one-office telephone system, if the growth is more rapid than anticipated, as it often is, or if the growth of the city takes place in an unexpected direction, as it frequently does, it becomes necessary to remodel the cable and wire plant to suit the new distribution of business.

A one-office telephone plant sometimes must be almost entirely rebuilt within a few years of its installation in order to adapt it to a shifting of population, or to make it adequate for the customers unexpectedly demanding service.

With a multi-office automatic system this need not be done. If an unexpected demand for telephones develops in a certain section of the city, it is not necessary to put in more conduits and cables or to replace present cables with larger ones to take care of the demand, but the situation is readily and practically met by putting in a substation or a branch office in the congested district. The present line cables running to the district may be used as trunk cables to the new office. Thus the traffic carrying capacity of the cable and conduit plant reaching any district may be greatly multiplied without any additional expenditure for cable or duct. Consequently, one of the most attractive features of an automatic multi-office system is that it affords a stable value to the investment in wire, cable, and conduit.

A paper to be presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N.J., June 29—July 2, 1908.

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THE MEASUREMENT OF ROTARY SPEEDS OF DYNAMO MACHINES BY THE STROBOSCOPIC FORK

BY A. E. KENNELLY AND S. E. WHITING

It is the object of this paper to call attention to what has already been accomplished by others in the direction of measuring rotary speeds with the stroboscopic fork, and also to a certain new modification of the principle which has been developed by the authors.

Definition. A stroboscopic fork consists essentially of a tuning fork, such as is shown in Fig. 1, carrying at its extremities a pair of thin strips, or flat shutters, in the plane of vibration. A narrow slit is cut in each shutter parallel to the fork's length. These slits lie opposite to each other when the fork is at rest, so as to permit an observer to see through both slits in this condition. When the fork is thrown into free vibration, the line of vision is interrupted by the vibrating shutters, except during a very brief interval once in each alternation, or twice in each complete cycle, of the fork's vibration, when the slits pass each other, moving rapidly in opposite directions. If then the fork makes say 60 alternations per second, corresponding to a vibration frequency of 30~, there will be 60 brief visual stimuli per second admitted to the retina of the observer's eye. If the object under inspection through the shutters is rotating in such a manner that consecutive retinal images are similar and symmetrical, the picture apprehended by the observer will be continuous and stationary; that is, the object will appear to stand still. Moreover, a certain cyclic range of departure from strict uniformity in the successive images formed on the retina will give an impression of a continuously rotating picture.

If the appearance presented by a rotating object is stationary, when viewed through a stroboscopic fork, we know that the speed of the object's rotation is constant, and also that it bears some simple numerical relation to the speed of vibration of the fork. Since the rate of a tuning fork's vibration is remarkably constant, is nearly independent of temperature changes, and can be determined once for all with great precision, the speed of rotation under inspection becomes known with a like degree of precision.

Brief historical outline. The stroboscopic fork has been known and used by physicists for some time. It has been used, for example, in the Lorenz method of determining the absolute value of the ohm.[1] In the Lorenz apparatus, a stroboscopic fork has been used to measure the speed of rotation of a small driving motor to within one one-hundredth of one per cent. Although stroboscopic methods have been used to some extent in engineering tests, the stroboscopic fork has only recently been employed for measuring the speeds of dynamo machinery. The stroboscopic fork was described in this connection in a paper on "Stroboscopy", by Dr. Charles V. Drysdale, read at the Optical Society London in 1905, and shortly afterwards reprinted.[2] Figs, 1, 2 and 3 are taken from that paper. The tuning fork he employed was like that in Fig. 1, held in the observer's hand and excited into vibration at suitable intervals, by mechanical impulses, such as a light blow on the knee. The vibration frequency of the fork was 50 cycles per second, or 6000 peeps per minute. The target shown in Fig. 2 was mounted concentrically on one end of the rotating shaft whose speed was required to be measured. At every 100 revolutions per minute of the shaft, (*i.e.* 100, 200, 300, etc., rev. per min.), the serrated edge pattern of this rotating target would appear stationary. Moreover, at certain speeds, the square, the pentagon, and the hexagon would severally appear stationary. Fig. 3 represents

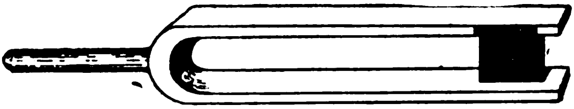

FIG. 1—Stroboscopic fork

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[1] "Absolute Measurements in Electricity and Magnetism", by A. Gray, London, 1893, Vol. II, page 594.

[2] "The Optician and Photographic Trades Review", Dec. 8 and 15, 1905.

the retardation speed-time curve of an unloaded motor, after switching off, obtained by stroboscopic-fork observations.

A paper on "Accurate Speed, Frequency and Acceleration Measurements," by Dr. Drysdale, appeared in the "*Electrical Review*," of London, for September 7 and 14, 1906. Figs. 4, 5, and 6 are taken from that paper, which describes an electrically driven fork, as seen in Fig. 4, the details being given by Dr. Drysdale in Fig. 7. The standard vibration frequency is 50 cycles per second, and the target described was the same as in the previous paper, Fig. 2. Fig. 5 illustrates the device for calibrating the fork. This fork, *F*, is mounted in front of a small shunt motor that can be accurately controlled in speed with the aid of the hand rheostat, *R*. The motor is driven in synchronous relation with the fork, as evidenced to the observer by the standstill of the pattern on the target, *T*. The revolution-counter, *C*, geared with the motor shaft, is then allowed to register for say ten minutes by a stop-watch; so that the record of the counter, *C*, during that time enables the uniform speed of the motor, and of the fork, to be determined closely.

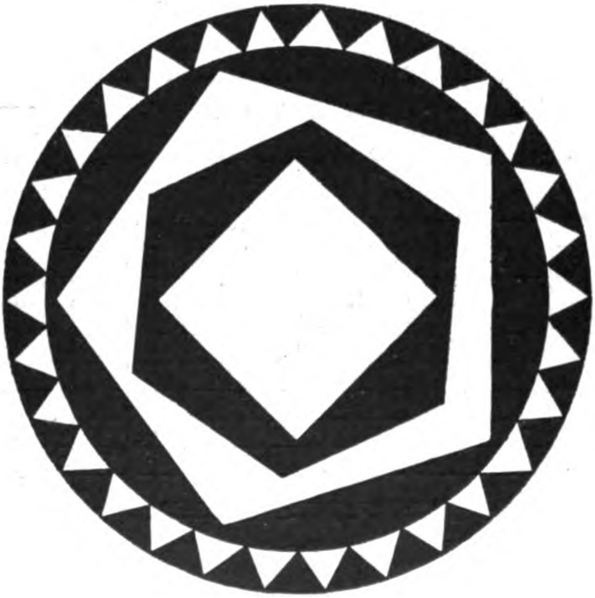

FIG. 2—Stroboscopic target

For rotary speeds intermediate between those at which the target patterns appear to stand still, the simple stroboscopic fork of Figs. 1, 5 and 7 can only serve to measure speeds indirectly, by enabling the observer to count the apparent revolutions of the target image during say one minute by the watch. For example, if the motor's speed was say 1200 rev. per min., the target, viewed through the fork, would appear stationary; but if the speed increased to 1220 rev. per min., the target would appear to rotate 20 times per minute in the direction of motion. It is desirable for many purposes, however, to bring the picture of the target to a standstill at any or all steady speeds within the ordinary range. Dr. Drysdale effected this in the manner indicated in Fig. 6. The conical roller, *R*, was driven by a sort of direct-current synchronous motor, *M*, which in its turn was operated by current impulses from the electrically driven standard fork. A thin disc, *D*, with radial slots, runs on the surface of the conical roller; so that by moving the disc from the smaller to the larger end of the cone, the speed of the disc's rotation could be increased and regulated very definitely. In this way the number of peeps per minute can be brought into synchronous relation with the number of revolutions per minute of a target on a rotating shaft under observation, and the coincidence is rendered manifest by the picture of the target pattern becoming stationary, when viewed through the rotating slots.

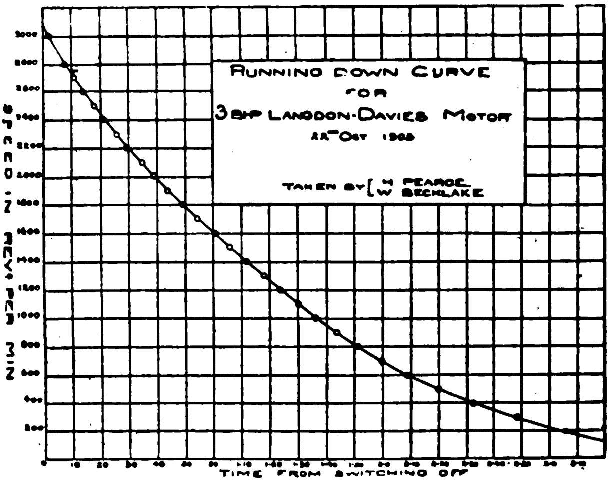

FIG. 3

Dr. Drysdale's paper set forth the advantageous application of the stroboscopic fork to the measurements of acceleration, retardation, uniformity of speed, frequency and slip.

The stroboscopic fork has also been employed in the United States by Dr. Northrup for adjustably varying and controlling the speed of a small alternating-current generator or converter.

The convenience and precision of the method employed by Dr. Drysdale was observed by one of the writers of this paper on the occasion of a visit to the Northampton Institute, London, in 1907. The writers believe that his method only requires to be more generally known in order to be used extensively. A simple stroboscopic fork, such as is shown in Fig. 1, selected for the right frequency, is sometimes capable of being used as a speed measurer of an engine, or as a frequency measurer of an alternator, without even the use of a special target, by watching the spokes of its flywheel, in a fairly good light, through the slits of the fork. Such a fork can maintain a satisfactory amplitude of vibration for more than half a minute at a time after being set in vibration, is very portable, simple, and not easily deranged, under ordinary care.

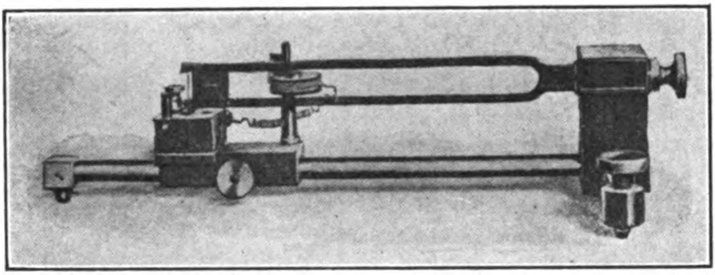

FIG. 4—Electrically driven tuning fork, with slits

New modification of the stroboscopic fork. The great advantage of the stroboscopic fork is that when it is vibrating in synchronous relation with the rotating target, the latter appears stationary, and very small changes in speed may then be readily detected. For example, if the target on the rotating shaft makes 1200 rev. per min., and appears stationary through the fork slits, an increase or diminution of one rev. per min., or one-twelfth of one per cent. in the speed, would cause the picture to rotate once per minute forwards or backwards respectively, a rate of rotation that is readily capable of being noted by the observer. The difficulty is that, in practice, the speed to be measured is seldom in exact synchronous relation with the fork. If the target has such a pattern that its picture becomes stationary at each and every 100 revolutions per minute, the speed to be measured may lie anywhere between the century limits, and the fork is unable to make the picture stationary. As already mentioned, Dr. Drysdale has met this difficulty by the use of a conical roller with stroboscopic disc, and this may be a satisfactory solution of the problem for use in the laboratory with a stationary apparatus; but the conical roller device is not portable.

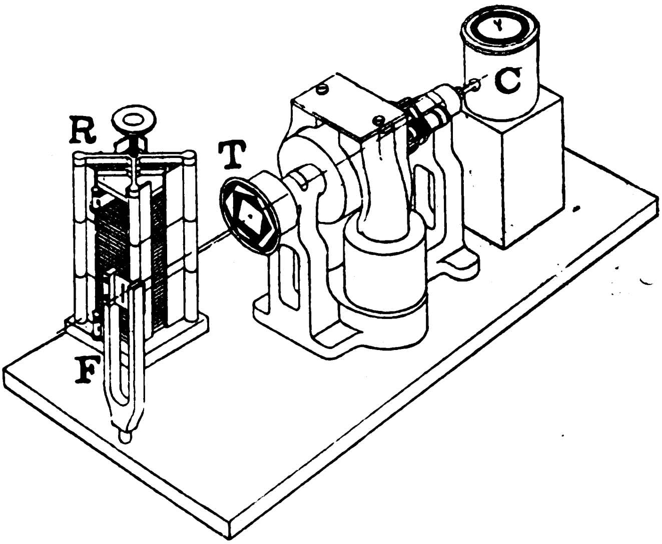

FIG. 5—Calibrating device

The writers have succeeded in arriving at a portable type of stroboscopic fork, which admits of being adjusted in its rate of vibration through a range of about 5% either above or below its mean value, continuously, and without sensibly disturbing the motion. For this purpose a pair of sliding weights grip the sides of the fork friction tight, and can be moved gradually from one position to another within a range of about 7½ inches (19 cm.) by a pair of strings passing over guide-pulleys, and normally slack.

The instrument is shown in perspective in Fig. 8. Its details, in plan, elevation, and end views appear in Fig. 9.

Details of construction. Referring to Fig. 9, the fork *A* is made of a strap of vulcan tool steel 36.7 in. (93.0 cm.) long, 1 in. (2.54 cm.) wide, and $\frac{3}{16}$ in. (0.475 cm.) thick, weighing, without attachments, 1.925 lb. (873 gm.). The over-all length of the fork along its midplane is 18 in. (45.8 cm.). The reason for using so long a fork was to produce a low-frequency vibration, or a fork speed comparable with the speeds ordinarily met with in rotating machinery.

The fork is mounted on a base-plate of cast aluminum by an aluminum clamp with a steel screw $\frac{1}{4}$ in. (0.64 cm.) in diameter. The free ends of the fork carry a pair of thin sheet-steel shutters with slits 0.59 in. (1.5 cm.) long and 0.008 in. (0.2 mm.) wide. There are small brass screw adjustments for bringing these slits accurately in conjunction when the fork is at rest, and there are also small brass screw clamps, with copper washers, for clamping the shutters in this position. The fork can be tuned to the required normal frequency by small brass weights clamped on pins set into the free ends of the prongs, near *C*.

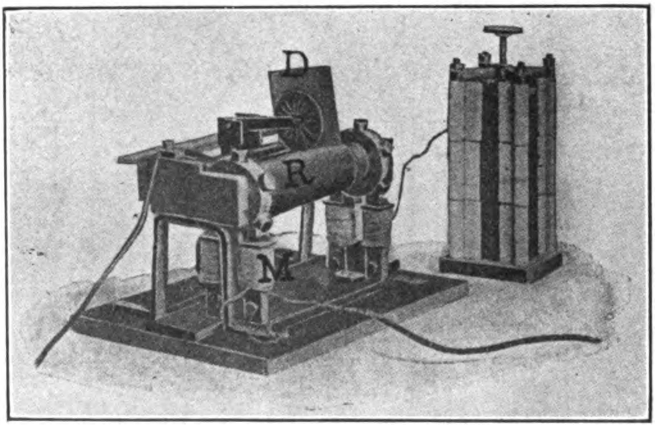

FIG. 6--Roller stroboscope

The sliders, *B*, are rectangular pieces of cast iron, milled out to travel smoothly over the fork, and closed by brass plates on the outer sides of the prongs. The brass covers are provided with recesses $\frac{1}{8}$ in. ($\frac{1}{3}$ cm.) deep, into which fit bent strips of clock-spring, 1 in. (2.5 cm.) long and $\frac{3}{8}$ in. (1 cm.) wide. These springs rest with their two ends pressing against the outer surfaces of the prongs, and prevent the sliders from moving when the

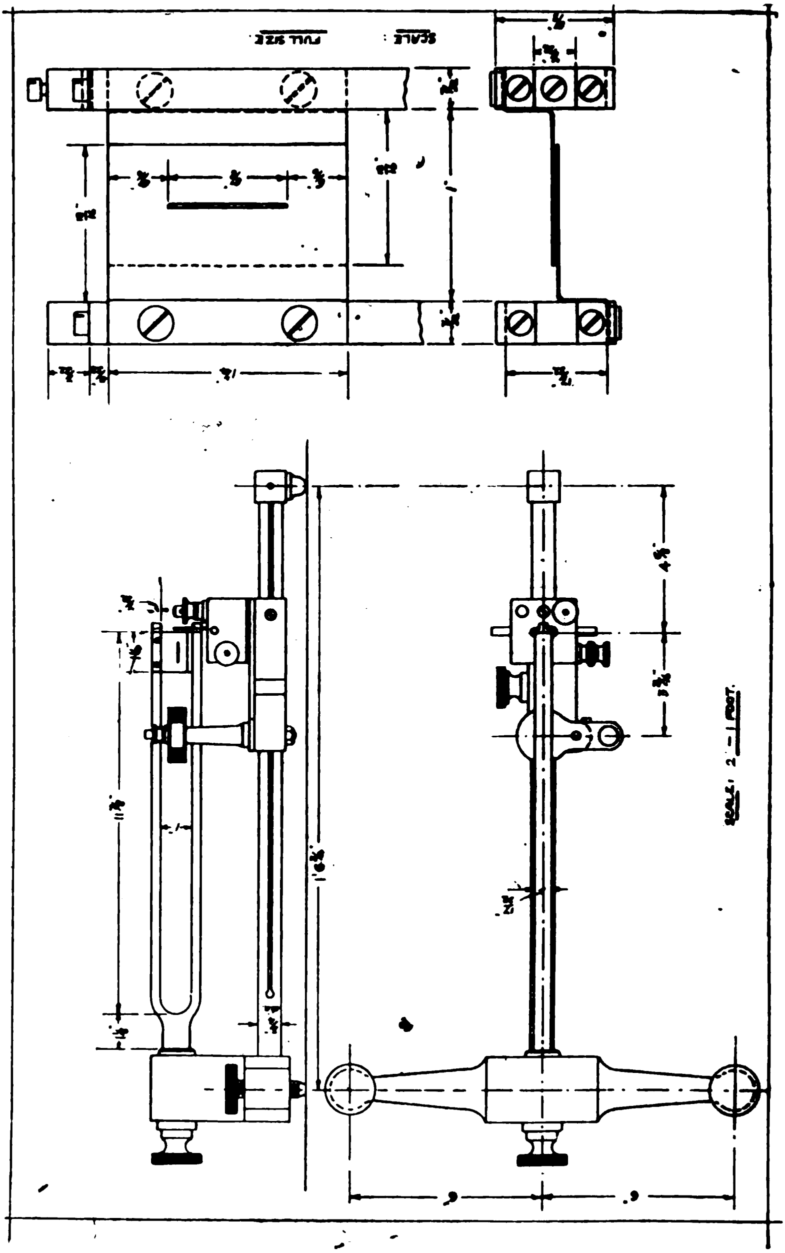

FIG. 7.—Details of Drysdale fork

fork is held upright. At the same time the sliders do not grip the prongs so tightly but that they are readily slid along by strings which are fastened to them. These strings pass over guide-pulleys of aluminum, some on the base and others on the prongs, and are clamped under screws carried by the aluminum wheels *J*, near the apex of the fork. The strings lie normally slack, and vibrate with the fork. Tension is applied in either direction by the hand of the observer on one of the wheels *J*. The wheels are clamped on a common shaft in such a manner that they exert equal and symmetrical tensions on the two strings and pull the sliders along evenly. The sliders carry pointers that move over graduated scales, from which the speed of the fork can be read directly.

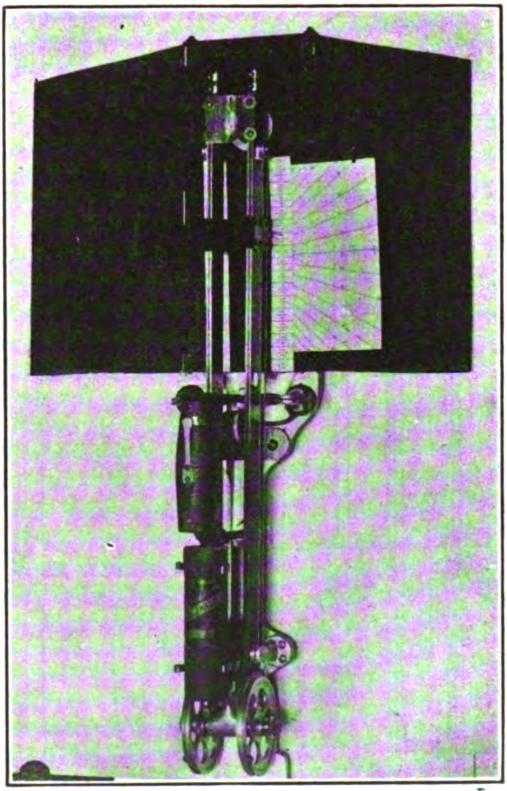

FIG. 8—Perspective view of variable-frequency fork

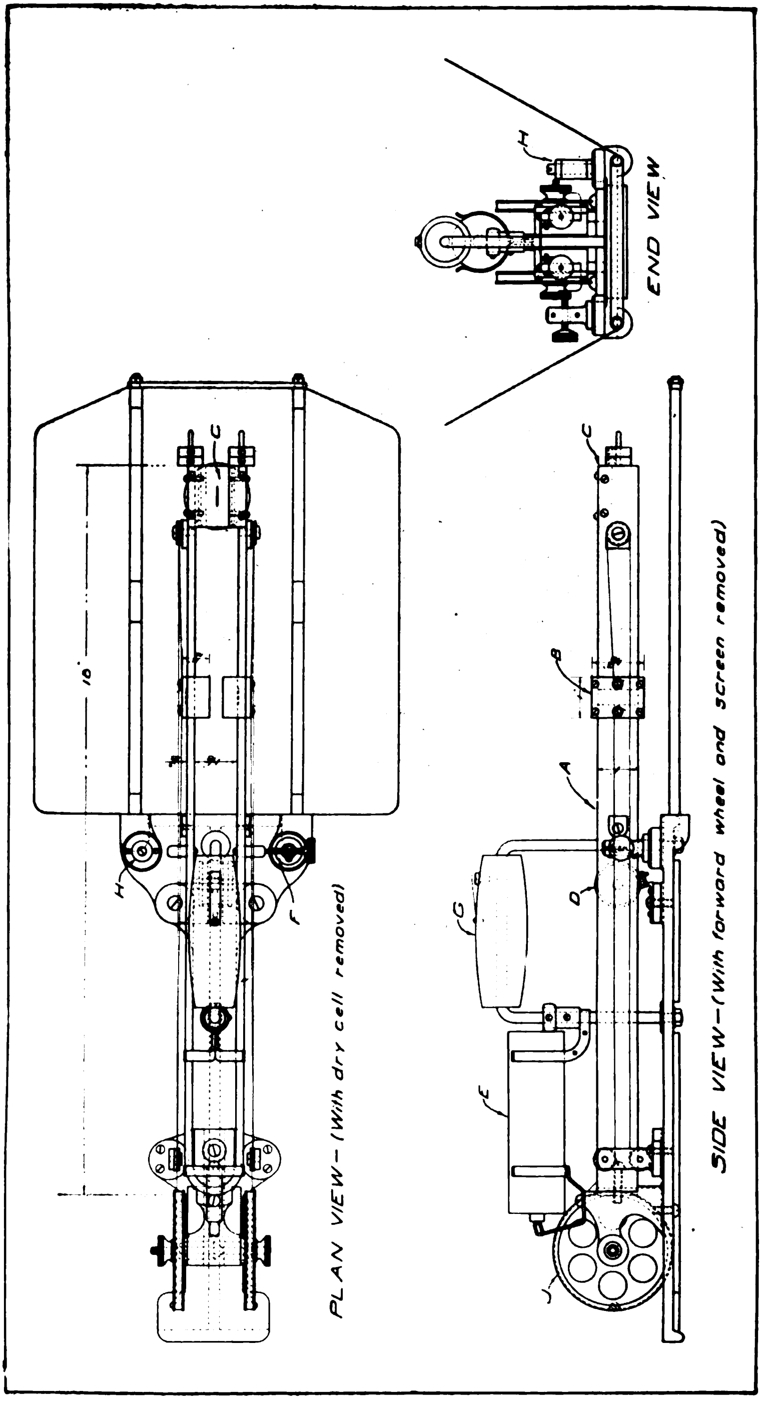
END VIEW
H
PLAN VIEW—(With dry cell removed)
C
10"
H
F
SIDE VIEW—(With forward wheel and screen removed)
C
B
A
D
G
E
J

Fig. 9—Details of variable-frequency fork

The fork is driven by the electromagnet, *D*, held between the prongs in a brass sleeve, mounted on an adjustable aluminum sole-plate. The electromagnet spool carries 15 layers, each of 35 turns of enameled copper wire 0.0165 in. (0.42 mm.) enameled to 0.018 in. (0.456 mm.), and offering a resistance of about 3.25 ohms. There is a very light steel spring fastened to each prong near the electromagnet, and one of these springs is used to open and close the circuit by a platinum-tipped contact, vibrating against the tip of an adjustable milled-head brass screw, *F*, set in an insulated aluminum split post. The resilience of the contact spring must have no appreciable effect on the speed of the fork, as is easily tested by watching a synchronously rotating target while turning the axis of the fork slowly by the handle. In order to suppress sparking at the vibrating contacts, a spool *H*, carrying a few feet of insulated german-silver wire, of about 70 ohms resistance, is connected permanently in shunt to the contacts. Current is supplied to the electromagnet from a single dry cell of standard type, having an electromotive force of 1.45 volts, and an internal resistance of about one-third ohm. The average current strength used in operating the fork is about 0.15 ampere. The dry cell, *E*, is held in spring clips, in such a manner that inserting the cell into the clips automatically inserts the cell into the circuit, or effects the necessary electric connections. The amplitude of vibration of the prongs of the fork is about $\frac{1}{8}$ in. (3.2 mm.) at the slits, on each side of the zero position, or position of rest, which produces a maximum cyclic velocity of about 1 foot (30 cm.) per second at the normal speed of the fork. Since the slits pass each other travelling in opposite directions their relative velocity is about 2 feet (60 cm.) per second, and the duration of each peep through the slits will be one three-thousandth second, or one one-hundred-eighty-thousandth minute. A target rotating at 1800 rev. per min. will only move through one one-hundredth of a revolution during each peep, and since the pitch of the teeth on the outer edge of the target is one-eighteenth of revolution, the blurring of the visual image, due to the motion during the intervals of vision, will only be about one-sixth of the pitch. The blurring is not troublesome if the motion during each peep is distinctly less than one-half of the pitch in the pattern under examination. The higher the speed of rotation, therefore, the greater must be the speed of the slits, either by increase of vibration amplitude or increase of frequency, and the narrower must be the slits, other things being equal. The same result will be produced, however, at high steam-turbine speeds, by using targets of smaller number of teeth in the pattern, so as to increase the pitch.

The instrument is held by the handle, *G*. The handle carries a small contact key, which is closed by the hand grasp, for automatically interrupting the voltaic circuit when the apparatus is laid aside. The weight of the instrument complete as seen in Figs. 8 and 9 is less than 6 lb. (2.65 kg.).

A pair of brass rods support aluminum sheets that shield the observer's eye from extraneous light when looking through the slits. The sheets also carry the scales for reading off the speed of the fork, and they fold over the prongs so as to cover the slits when the fork is out of service.

Process of observing. In order to make a measurement, it is necessary to fasten the target concentrically upon an end of the rotating shaft whose speed is required to be ascertained. Cement, or soft sealing wax, will serve for a dynamo- or motor-shaft. A shaft that runs warm, and has an oily surface, is hard to apply cement upon. In such cases, a metallic spring clip has been used. When neither end of the shaft projects from a bearing, it is difficult to fasten the target on. Sometimes, however, the spokes of the wheels on the shaft will serve as a target. If not, it may be necessary to mount the target on a light auxiliary shaft in bearings, and drive a pulley on the same from the shaft which is without projecting ends, by an endless tape belt, so as to bring the speed of the target into definite relation to the speed of the shaft under test.

The target should receive good daylight illumination. In the absence of such natural illumination, excellent results can be secured from a single 16 candle-power lamp and opaque reflecting shade, supported near to the target, so as to throw on its surface an illumination of about 25 foot-candles (300 meter-hefners).

The observer takes a convenient position facing the revolving target, holds the fork in his left hand, with the prongs vertical, and looks through the slits. If he is sitting, he rests the aluminum foot of the baseplate on his knee. He then moves the wheels with his right hand, until one of the patterns on the target, preferably the external one, comes to a standstill. He then reads the speed from the scale.

Target. After many experiments on different sizes, colors and patterns of target, the writers have selected in preference that shown in Fig. 10, bearing white markings on a black ground. Its diameter is 9.5 in. (24.2 cm.). It is made, with advantage, on paper, with the aid of a stencil, and pasted on a backing disc of cardboard, pasteboard, or sheet metal, for mounting on the rotating shaft. It will be seen that it differs only in minor details from the target indicated in Dr. Drysdale's earlier paper, (Fig. 2).

If the pattern on a rotating target has a positions of symmetry per revolution, and makes n revolutions per unit of time, and if the speed of the fork's vibration is such that it provides p peeps per unit of time, then the pattern will appear stationary through the fork when $(a\,n)$ and p are in integral numerical relation. Ordinarily, $(a\,n)$ is greater than p; so that standstill occurs in the picture when $\frac{a\,n}{p}$ is any integer. For instance, either a pentagon or a five-pointed star, rotating about its center of figure, has 5 positions of symmetry per revolution. If the

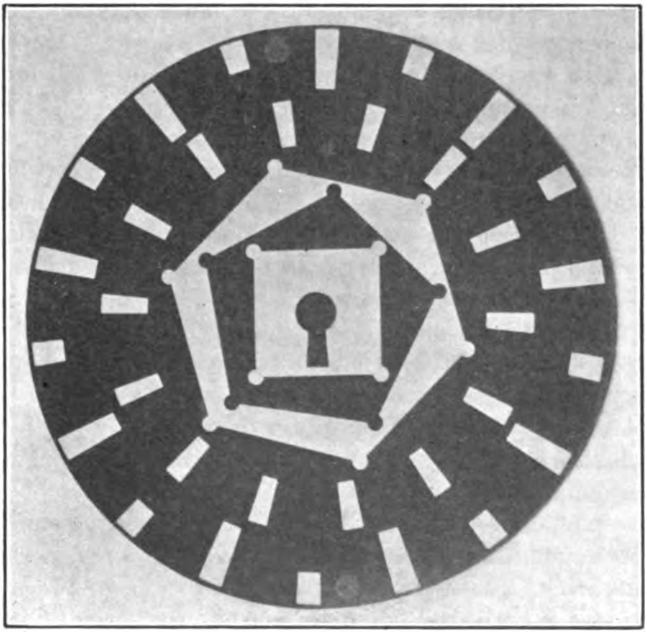

FIG. 10 –Target for use with variable-frequency fork

fork gives $p = 1800$ peeps per minute, and the speed of rotation is say just $n = 1080$ revs. per min., then $\frac{a\,n}{p} = \frac{5400}{1800} = 3$, an exact integer, and the picture will appear stationary. Moreover, the pentagon will be moving through three positions of symmetry, or 216°, between successive peeps.

The target of Fig. 10 contains a square, a pentagon, a hexagon, a 14-point star, and an 18-point star. The fork has a mean speed giving 1800 peeps per minute. The square, having 4 positions of symmetry, will appear stationary at 450, 900, 1350, 1800, 2250, 2700, 3150, or 3600 rev. per min., that is, at every 450 rev. per min. or quarter of synchronous speed. Moreover, the image of the square will appear doubled, although fainter, at the intermediate speeds of 225, 675, 1125, etc., rev. per min.; that is at every 225 rev. per min., or eighth of synchronous speed.

The pentagon, with 5 positions of symmetry per revolution, will stand still at every 360 rev. per min., or fifth of synchronous speed. It also appears stationary, doubled but less plainly, at every 180 rev. per min., or tenth of synchronous speed.

The hexagon, with 6 positions of symmetry per revolution, will stand still at every 300 rev. per min., or sixth of synchronous speed. It doubles and will stand still at every 150 rev. per min., or twelfth of synchronous speed.

The 14-point star, with 14 positions of symmetry per revolution, will stand still at every 128.6 rev. per min., or fourteenth of synchronous speed.

The 18-point star, or external circle, with 18 positions of symmetry per revolution, will stand still at every 100 rev. per min., or eighteenth of synchronous speed. Since nine of the points are long, and intermediate points are short, the series of 18 will be stationary and clear for even hundreds, and stationary but blurred on the inner edge, for odd hundreds of rev. per min.

The reason for selecting the above described particular set of target patterns is that it includes the following series of integral values for a:

1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, and 18. In other words, standstill of some pattern will be produced with the normal fork speed at any half, third, fourth, fifth, sixth, seventh, eighth, ninth, tenth, twelfth, fourteenth, or eighteenth of synchronous speed. In addition to this, the speed of the fork can be varied adjustably within a range of 5% above or 5% below normal. This is sure to bring some pattern to standstill at any except very low speeds of rotation. By means of a graphic chart, and a little examination of the pattern, the speed of rotation can be read off directly from the pointers on the sliders. A displacement of 1 mm. (0.0394 in.) corresponds, on the average, to a change in fork speed of about 1.25 peeps per minute, or less than one-tenth of one per cent.

The scale of speed variation with slider displacement is not evenly graduated. The successive intervals correspond to an equation of the second degree. The distance that must be moved for a change of one revolution per minute is about 20% greater when the sliders are approaching their limit near the middle of the prongs, than near their limit towards the end of the prongs. This means that the scale must be prepared from a suitable number of calibrating observations. The simplest way to calibrate the scale is to keep the speed of the rotating target constant, by the control of an observer with an auxiliary fork, and to count the number of revolutions per minute of the image through the calibrated fork, with a stop watch, as the sliders are shifted from point to point along the scale, say 1 cm. at a time.

Applications of the instrument. As pointed out in Dr. Drysdale's papers, the stroboscopic fork is a very convenient instrument for measuring speeds with precision, and particularly for measuring small variations of speed. The device is, in effect, a speed-variation microscope. The instrument is useless when the speed is rapidly varying through a wide range in an irregular manner, except that it gives in such cases ample qualitative evidence of such irregularity. Cyclic variations of speed, as in the hunting of a synchronous motor, if not too rapid, can be measured by observing the angle of oscillation of the target pattern. Variations in the frequency of an alternator, or of slip in a motor, can be observed with ease. There is something fascinating in the pictures presented by the instrument, which are very striking when observed for the first time.

Limits of accuracy in the use of the apparatus. The degree of accuracy of the simple stroboscopic fork is remarkably high, and of the order of one part in ten thousand. The variation of fork speed with temperature is about 0.01 per cent. per degree cent. according to measurements reported.[3] In the fork with adjustable sliders described in this paper, the degree of precision in speed is reduced to some extent, owing to errors in the parallel movement of the two sliders, and to errors in reading off their position along the scale. Nevertheless, the degree of accuracy remaining is much greater than is ordinarily needed in engineering measurements. Moreover, the degree of accuracy with which *slow* variations in speed can be observed is as high in the fork with adjustable sliders, as in the simple fixed fork. At 1800 rev. per min., it is easily 1 part in 1800, and it increases in direct proportion with the speed.*

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[3] Electrical Review article, Sept. 1906.

So far as the writers are aware, there is no patent on the method of measuring speeds here described, and it is free to all users.

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*The writers desire to express their indebtedness to Dr. Drysdale, not only for the matters appearing in his papers, but also for illustrations and suggestions directly received from him.

A paper presented at a meeting of the Philadelphia Section of the American Institute of Electrical Engineers, Philadelphia, Pa., February 10, 1908.

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THE SINGLE-PHASE COMMUTATOR-TYPE MOTOR

BY B. G. LAMME

The broad statement may be made that it is no more difficult to commutate an alternating current than an equal direct current. Such a statement would appear to be entirely contrary to the usual experience, but a little study of the matter will show where the apparent discrepancy lies. In commutator type alternating-current motors, as usually built, a relatively large number of commutator bars pass off under the brush during one alternation of the supply current. While the current supplied is varying from zero to maximum value and back to zero, possibly 50 bars have been passed under the brush, and therefore 50 coils in the armature have been reversed or commutated. Some of these reversals occur at the top of the current wave which has a value of about 40% higher than the mean or effective value which is read by the ammeter. The motor is therefore at times commutating 40% higher current than that indicated by the instruments. It is thus evident that in comparing the commutation of 100 amperes direct-current with 100 amperes alternating-current we should actually compare the direct-current with 141 amperes alternating. In other words, for commutating equal currents alternating-current or direct-current, the alternating-current ammeter should register only 71% as much current as the direct-current. Another way of expressing it is that we have to commutate the top or maximum of the alternating-current wave, while our instruments only record the mean value.

If the above represented the only difference between the alternating current and direct current the problem to be solved in commutation of alternating current would not be serious.

However, the current to be commutated by an alternating-current motor is not merely the working current supplied to the motor and measured by the ammeter, but there is, in addition, a current which is generated in the motor itself, both at standstill and during rotation, which has to be reversed or commutated along with the working current. It is this latter current, usually called the local or short-circuit current, which has been the source of greatest trouble in commutating alternating current; for this short-circuit current may have a value anywhere from three to ten times the working current, depending on the design of the machine. Therefore in comparing the commutation of an alternating current, as indicated by an ammeter.

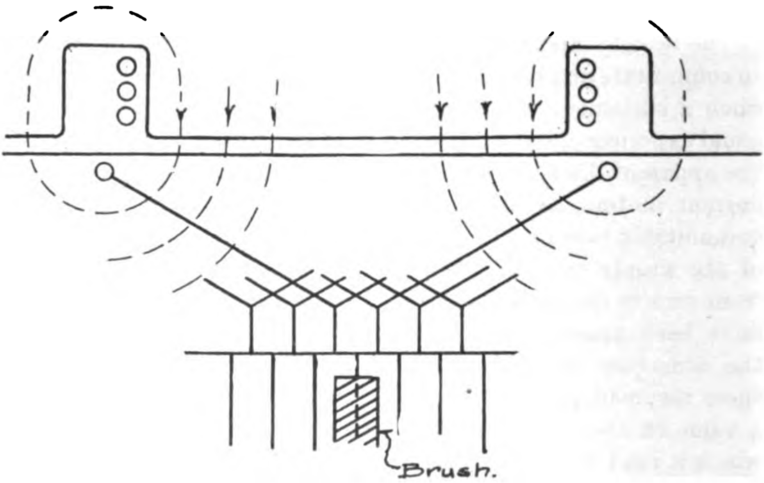

FIG. 1

with an equal direct current, we should, in reality, consider that the alternating-current motor is commutating a maximum current from five to ten times the value of the indicated current. Furthermore, it would not do to reduce the ammeter current to one-fifth or one-tenth value in order to compare commutation with direct current, because by so doing we would simply be reducing the small applied component of the total current commutated by the brushes, the local or short-circuit current still retaining a rather high value. In order to compare with direct-current commutation, it would be necessary for the total maximum of the combined supply and the short-circuit current to be reduced to the same value as direct current.

It is the local current in the armature turn short-circuited by the brush which is the source of practically all the trouble in commutating alternating currents. Fig. 1 illustrates a portion of the field and armature structure of a commutator type alternating-current motor. It will be noted that the armature conductor, which is in the neutral position between poles, surrounds the magnetic flux from the field pole, just as the field turns themselves surround it. The field flux being alternating, this armature turn will have set up in it an electromotive force of the same value as one of the field turns. Short-circuiting the two ends of this armature turn should have the same effect as short-circuiting one of the field turns, which is the same thing as short-circuiting a turn on a transformer. Such a short-circuited turn, if of sufficiently low resistance, should have as many ampere-turns set up in it as there are field ampere-turns. In single-phase motors of good design the field ampere-turns per pole are about twelve to fifteen times the normal ampere-turns in any one armature coil. Therefore, if the armature coil in the position shown in this Fig. 1 should have its ends closed on themselves the current in this coil would rise to a value of twelve to fifteen times normal. In reality, it would not rise quite this much, because this armature turn is placed on a separate core from the field or magnetizing turns with an air-gap between, so that the magnetic leakage between the primary (or field winding) and this armature (or secondary winding) would tend to protect this coil somewhat, just as leakage between the primary and secondary windings of a transformer tends to reduce the secondary electromotive force and current. Also, this armature coil is embedded in slots, thus adding somewhat to its self-induction, and tending further to reduce the short-circuit current. In consequence, with its ends closed together the current in this armature coil would probably not rise more than ten to twelve times above normal value under any condition. It is evident, therefore, that if the brush shown in Fig. 1 as bridging across two commutator bars to which the ends of this coil are connected is of copper or other low-resistance material, then there could be an enormous local current set up in the coil when thus short-circuited by the brush. This local current of about ten times the normal working current would have to be commutated as the brush moves from bar to bar, and therefore the operation of the machine would be similar to that of a direct-current motor if overloaded about ten times in current. In other words, there would be vicious sparking.

Even if the low-resistance brush were replaced by one of ordinary carbon, the short-circuiting current would still be relatively high, due to the fact that it is not possible to make the brush contact of very high resistance by reducing the size or number of the brushes, because these same brushes must carry the working current supplied to the motor, and there must be brush capacity sufficient to handle this current. This brush capacity will, in practice, be of such amount that the resistance in bridging from one bar to the next is still rather low, although much higher than if a copper brush were used. Experience shows that with not more than four or five volts generated in this short-circuited coil by the field flux, the resistance of the carbons at the contact with the commutator would be such that a short-circuit current of three to four times the normal working current in the coil can still flow. Therefore, if the motor were equipped with carbon brushes and had but four or five volts generated in the short-circuit coil, the motor would have to commutate the main or working current and also a short-circuit current of possibly three times the amount. This short-circuit current would also have a maximum or top of its current wave. Assuming 100 amperes as the current supplied to the motor, the machine therefore actually commutates a supply current of 141 amperes and an additional short-circuit current of possibly three times this value, or from 400 to 500 amperes; therefore, the motor actually commutates the equivalent of about 600 amperes direct current when the alternating-current ammeter is reading 100. It is evident from this that any one who tries to commutate alternating current with an ordinary type of commutating machine would at once draw the conclusion that alternating current in itself is very difficult to commutate, naturally overlooking the fact that it is the excessive current handled by the brush that is back of the trouble, and not the current indicated by the ammeter.

From what has been stated, it is evident that the excessive local current is back of the difficulty in commutating alternating current. All efforts of designers of alternating-current commutator motors have been in the direction of reducing or eliminating this local current. The present success of the motor, in the various forms brought out, is largely due to the fact that this current has been successfully reduced to so low a value that it does not materially add to the difficulties of commutating the main current. No successful method has yet been practically developed for entirely overcoming the effects of this short-circuit current under all conditions from standstill to highest speed. Some of the corrective methods developed almost eliminate this current at a certain speed or speeds, but have little or no corrective effect under other conditions; other methods do not effect a complete correction at any speed, but have a relatively good effect at all speeds and under all conditions. The former methods would appear to be applicable to motors which run at, or near, a certain speed for a large part of the time; the latter method would be more applicable to those cases where the motor is liable to be operated for considerable periods with practically any speed from standstill to the highest. While several methods have been brought forward for correcting local current when the motor has obtained speed, yet up to the present time but one successful method has been developed for materially reducing this current at standstill or very low speeds. It may be suggested that the short-circuit voltage per coil be reduced to so low a value, say four or five volts, that the local current is not excessive and does not produce undue sparking. This would certainly reduce the sparking difficulty, but is open to the very great objection that the capacity of the motor is directly affected by a reduction in the short-circuit voltage. This voltage per turn in the armature coil is a direct function of the value of the alternating field-flux and its frequency. Assuming a given frequency, then the short-circuit voltage is a direct function of the induction per field pole, and the lower the short-circuit voltage the lower must be the field flux. But the output of the machine, or the torque with a given speed, is proportional to the product of the field flux per pole by the armature ampere-turns. In a given size of armature the maximum permissible number of ampere-turns is pretty well fixed by mechanical and heating considerations, and therefore with a given armature the torque of the motor is a direct function of the field flux. Using the maximum permissible armature ampere-turns, the output of a given motor would be very low if the field flux were so low that the short-circuit voltage would not be more than three or four volts. Increasing the field induction, and therefore increasing the short-circuit voltage, increases the output.

Experience shows that on large motors, such as required for railway work, the induction per pole must necessarily be so high that the electromotive force in the short-circuit coil must be about double the figure just given; therefore, with such heavy flux the short-circuited current will necessarily be excessive unless some corrective means is used for reducing it.

I will consider the standstill or low-speed conditions first. For this condition only one practical arrangement has so far been suggested for reducing the local current to a reasonably low value compared with the working current. This method involves the use of preventive leads, or, as they are sometimes called, resistance leads. These consist of resistances connected between the commutator bars and the armature conductors. Fig. 2 illustrates the arrangement. The armature is wound like a direct-current machine, except that the end of one armature coil is connected directly to the beginning of the next without being placed in the commutator. Between these connections separate leads are carried to the commutator bars, and in these leads sufficient resistance is placed to cut down the short-circuit current. The arrangement is very similar in effect to the preventive coils used in connection with step-by-step voltage regulators which have been in use for many years. In passing from one step to the next on such regulators, it is common practice to introduce a preventive coil or resistance in such a way that the two contact bars are bridged only through this preventive device.

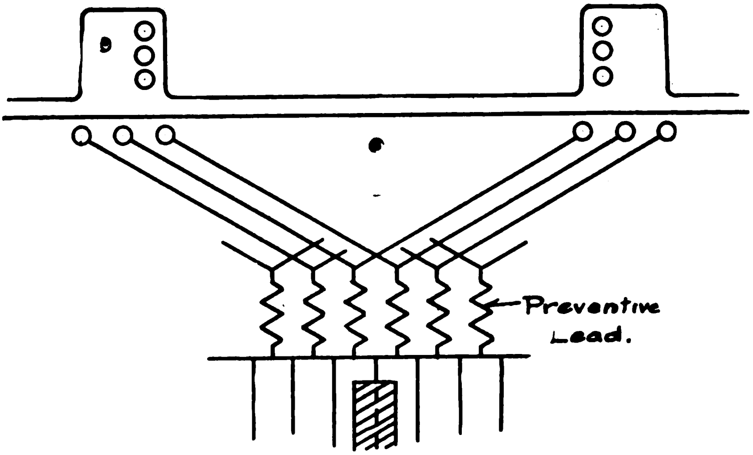

FIG. 2

In an armature winding arranged in this way, the working current is introduced through the brushes and the leads to the armature winding proper. After entering the winding, the current does not pass through the resistance leads because the connections between coils are made beyond these leads. In consequence, only a very small number of these leads are in circuit at any one time; when the armature is in motion all the leads carry current in turn so that the average loss in any one lead is very small. As the brush generally bridges across two or more commutator bars, there is usually more than one lead in circuit, but generally not more than three. When the brush is bridging across two bars, there is not only the working current passing into the two leads connected to these two bars, but there is the local current, before described, which passes in through one lead, through an armature turn, then back through the next lead to the brush. There are losses in these two leads due to these two currents. By increasing the resistance, the loss due to the working current is increased, but at the same time the short-circuit current is decreased. As the loss due to this latter is equal to the square of the current multiplied by the resistance, it is evident that increasing this resistance will cut down the loss due to the local current in direct proportion as the resistance is increased. When the working current is much smaller in value than the short-circuit current, an increase in the resistance of the leads does not increase the loss due to the working current as much as it decreases the loss due to the short-circuit current. Both theory and practice show that when the resistance in the leads is so proportioned that the short-circuit current in the coil is equal to the normal working current, the total losses are a minimum. Calculation, as well as experience, indicates that a variation of 20% to 30% at either side of this theoretically best resistance gives but a very slight increase in loss, so there is considerable flexibility in the adjustment of this resistance. The resistance of the brush contacts and of the coil itself must be included with the resistance of the leads in determining the best value. In practice it is found that with ordinary medium-resistance brushes, the resistance in the leads themselves should be about four or five times as great as the resistance in the brush contact and the coil; that is, we usually calculate the total necessary resistance required and then place about 70% or 80% of it in the leads themselves. When leads of the proper proportion are added to the motor, it is found that practically twice as high field flux can be used as before with the same sparking and burning tendency as when the lower flux is used without such leads. But even with six to eight volts per commutator bar as a limit, we are greatly handicapped in the design of the motors, especially when the frequency is taken into account. This limited voltage between bars also indicates at once why single-phase railway motors are wound for such relatively low armature voltages. Direct-current railway motors commonly use from 12 to 20 volts per commutator bar, or from 2 to 2.5 times the usual practice on alternating-current motors. With this low voltage between bars in alternating-current machines, with the largest practicable number of bars, the armature voltages become 200 to 250, or about 40% of the usual direct voltages. The choice of low voltage should, therefore, not be considered as simply a whim of the designers; it is a necessity which they would gladly avoid if possible.

Assuming preventive leads of the best proportions, let us again compare the current to be commutated in an alternating-current motor with that of the direct-current. Considering the ammeter reading as 100, the working alternating current has a maximum value of 140 and in addition there is a short-circuit current of same value. Even under this best condition, the alternating-current motor must commutate a current several times as large as in the corresponding direct-current motor. The design of such a motor, therefore, is a rather difficult problem, even under the best conditions.

While resistance leads theoretically appear to give the most satisfactory method for obtaining good starting and slow-speed running conditions, yet other methods have been proposed. The only one of any practical importance is that in which the short-circuit voltage is reduced at start and at slow speed by sufficiently reducing the field induction. As this reduced field induction would give a proportionately reduced torque, it is necessary at the same time to increase the armature ampere-turns a corresponding amount above normal. This is only a part solution of the problem, however, for the decrease in short-circuit current by this means is partly offset by the increase in the working current, so that the total current to be commutated is not reduced in proportion to the field flux. Where the period of starting and slow running is very short, this method is fairly successful in practice. However, with this arrangement it is rather dangerous to hold the motor at standstill for any appreciable length of time, for in such a case the large short-circuit current is confined to a single coil and the effect is liable to be disastrous if continued for more than a very short period. With this method of starting, the total current handled by the brushes will usually be at least two to three times as great as when preventive leads are used.

The preceding statements refer mainly to starting or slow-speed conditions. When it comes to full-speed conditions, however, there are various ways of taking care of the commutation. One of these methods is based on the use of preventive leads, as described; the other methods depend upon the use of commutating poles or commutating fields in one form or another.

It is evident, from what has been said, that at start the preventive leads which reduce the short-circuit current to low values will also be effective in a similar manner when running at normal speed. Such a motor with proper proportion of leads will, in general, commutate very well at full speed when the starting conditions have been suitably taken care of. Nothing further need be said of this method except that the tests show that the short-circuit current has considerably less value at high speed than at start.

The other methods of commutation at speed, involving commutating poles and commutating fields, necessarily depend upon the armature rotation for setting up a suitable electromotive force in the short-circuit coil to oppose the flow of the short-circuit current. As the electromotive force in the short-circuited coil is a direct function of the field flux, and is independent of speed, while the correcting electromotive force is a function of the armature speed, it is evident that either the commutating pole can produce the proper correction only at one particular speed, or the strength of this commutating pole must be varied as some function of the speed. Usually the strength of these poles is made adjustable with a limited number of adjustments and approximate compensation only is obtained on the average. In the Siemens-Schuckert motor the commutating poles are of small size and placed between the main poles. These are for the purpose of obtaining commutation when running. In addition the armature is provided with preventive leads for improving the operation at start and at slow speed. In the Alexanderson motor, according to published description, no separate commutating poles are provided, but the edges of the main poles are used as commutating poles, the armature coil having its throw shortened until its two sides come under the edges of the main poles. In this motor the field is weakened and the armature ampere-turns are increased while starting. The commutating-pole scheme in this motor is, in some ways, not as economical as in the Siemens-Schuckert arrangement, as the motor requires a somewhat higher magnetization with a consequent reduction in power-factor. The Winter-Eichberg motor is quite different in arrangement from any of those which I have mentioned. I will not attempt to describe this motor in full, but will say that it has two sets of brushes in the armature, one of which is short-circuited on itself, and carries the equivalent of the working current in the types I have described, while the other carries the magnetizing or exciting current which is supplied to the armature winding instead of the field. The arrangement is such as to give practically the same effect as a commutating pole or commutating field. When starting, the field flux is decreased and the armature ampere-turns increased.

All of the above motors are nominally of low armature voltage and all of them appear to commutate reasonably well at speed. Two of them use the full-speed induction at start, while the other two use reduced induction and increased armature ampere-turns at start.

There has been considerable discussion during the last year or two regarding the most suitable frequency for single-phase commutator type motors. It may therefore be of interest to consider what effect reduction in frequency would have on the commutation, output, and other characteristics of the motor.

The short-circuit voltage, as I have stated before, is a function of the amount of field flux and of the frequency. For a given short-circuit voltage the induction per pole can be increased directly as the frequency is decreased. If a certain maximum induction per pole is permissible at 25 cycles, then with 12.5 cycles, for example, the induction per pole may be double, with the same short-circuit voltage. This would at once permit double output if the saturation of the magnetic circuit would permit the doubling of the induction. But on 25-cycle motors, as usually built, we work the magnetic flux up to a point just on the verge of saturation, so to speak, as indicated in Fig. 3. It is evident that double induction, under such conditions, would not be practicable unless the 25-cycle motor had been worked at an uneconomically low point. However, an increase of 30% to 40% in the induction would appear to be obtainable, but a large increase in excitation is required. With but 30%

to 40% higher induction, and with the frequency halved, the short-circuit voltage would be but 65% to 70% of that with 25 cycles or, in other words, the voltage per turn in the field coil is but 65% to 70%. As the higher induction raises the armature counter electromotive force the field electromotive force can be increased in proportion for the same power-factor, or can be 30% to 40% higher than with 25 cycles. As the total field voltage, therefore, can be 30% to 40% higher, and the voltage per field turn is but 65% to 70%, it is evident that the number of field turns can be doubled without changing the ratio of the field inductive volts to the armature electromotive force. In other words, the field turns can be doubled if the frequency is halved. With the double field turns the field excitation can therefore be doubled, which is the requirement for the increased induction shown in Fig. 3. It is thus evident that halving the frequency will permit higher pole inductions, and therefore higher torque and output, with lower short-circuit voltage and better commutating conditions throughout. Also, this higher field induction is not necessarily accompanied by an increased iron loss, for the lower frequency of the alternating

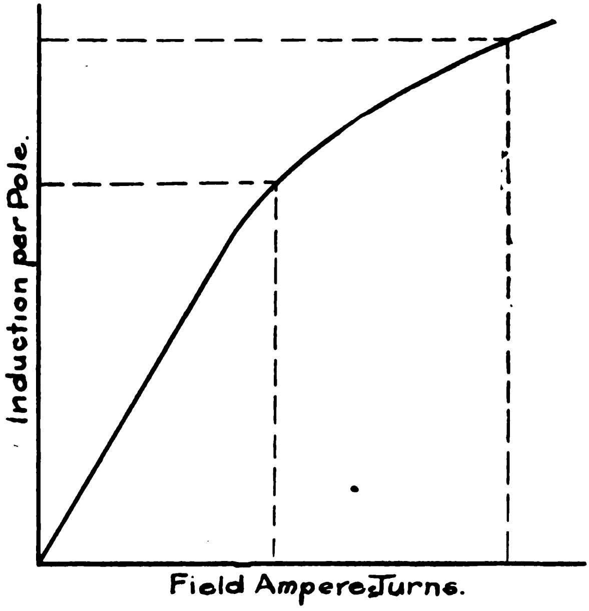

FIG. 3

flux compensates for this. On the above basis it may be asked why a reduction to 15 cycles is proposed instead of to 12.5, or even to 10 cycles. There are several reasons for the choice of 15 cycles.

1. The motor can be worked up to so high a saturation at 15 cycles that there is relatively small gain with a reduction to 12.5 cycles, which would be about the lowest frequency to consider when the transformers and other apparatus is taken into account.

2. As the torque of the single-phase motor is pulsating instead of being constant, as in a direct-current machine, there is liability of vibration as the frequency of the pulsation is decreased. This effect becomes more pronounced the larger the torque of the motor, and is, therefore, of most importance in the case of a large locomotive. Experience shows that this tendency to vibrate can be damped out effectively in very large motors with a frequency of 15 cycles, but becomes more difficult to suppress as the frequency is further reduced. This is, in reality, one of the fundamental reasons for keeping up to 15 cycles instead of reducing to 12.5 or lower.

3. The lower the frequency the heavier the transforming apparatus on the car or locomotive. It is probable that with 12½ cycles instead of 15 cycles, the increase in weight and cost of the transforming apparatus would about counter-balance the decrease in the same items in the motors themselves, although the efficiency and power factor of the equipment would be slightly better with the lower frequency.

4. As synchronous converters will be used to some extent in connection with the generating plants for single-phase systems in order to feed existing direct current railways, the frequency of 15 cycles will be slightly more favorable than 12.5 as regards cost of the converters and the step-down transformers. The same will be true if motor-generators are used for transforming to direct current, also for induction motors.

Against the choice of 15 cycles may be cited the fact that there are other frequencies which represent a better ratio to 25 cycles when frequency-changers are to be taken into account. A low-frequency railway generating plant may require to tie up with some existing 25-cycle or 60-cycle plant; this can be done by interposing frequency-changers. Or it may be desired to obtain a lower frequency with a single-phase current from some existing higher frequency polyphase plant. By interposing the frequency-changer the single-phase railway load will not exert any unbalancing effect on the polyphase supply circuit, and at the same time the railway circuit can be regulated up or down independently of the three-phase generator circuit. In case the three-phase plant is operated at 25 cycles, then a two-to-one ratio of frequencies; that is, 12.5 cycles on the railway circuit, would give the best conditions as regards choice of poles and speeds in the frequency-changer sets. A five-to-three relation is given by 15 cycles, which is not nearly as good as the two-to-one ratio. A frequency of 16⅔ cycles would give a three-to-two ratio, which represents considerable improvement over the five-to-three ratio. Therefore, this slightly higher frequency may prove of advantage in some cases. The choice of this frequency, however, does not mean a new line of apparatus; for a well designed line of 15-cycle motors tranformers, etc, should operate very well on a 16⅔-cycle circuit without any change whatever.

When transforming from 60 cycles, however, the 15 cycle gives a four-to-one ratio which is very good, and neither 12.5 nor 16⅔ cycles is very satisfactory. Therefore this 15-cycle frequency represents the best condition in transforming from 60 cycles, and fairly good conditions for transforming from 25 cycles; and by operation of 15-cycle apparatus at 16⅔ cycles a very good transformation ratio is obtained from 25 cycles. It may be of interest to recall that the old Washington, Baltimore and Annapolis Railway, which was the first road contracting for single-phase commutator motors, was laid out for 16⅔ cycles. There was considerable criticisms at that time of the use of this frequency, but the statement which I have just made shows one very good reason for this frequency. A second reason is that 16⅔ cycles per second is 2000 alternations per minute, which permits a steam turbine driving a two-pole generator to use a speed of 1000 rev. per min., which is a very good one for large turbo-generators.

I have gone into the question of induction and frequency as affecting the commutation and torque. I will now take up the question of power-factor in the single-phase commutator motor. In a direct-current motor we have two electromotive forces which add up equal to the applied electromotive force; namely, the counter electromotive force due to rotation of the armature winding in the magnetic field, and the electromotive force absorbed in the resistance of the windings and rheostat.

In the alternating-current motor there are these two electromotive forces, and there is also another one not found in the direct-current machine; namely, the electromotive force of self-induction of the armature and field windings due to the alternating magnetic flux in the motor. This inductive electromotive force exerts a far greater influence than the ohmic electromotive force for it has much higher values.

The inductive electromotive force lies principally in the main field or exciting winding of the alternating-current motor. There is a certain voltage per turn generated in the field coils, depending upon the amount of the field flux and its frequency, as stated before. This electromotive force per field turn is practically of the same value as the short-circuit electromotive force generated in the armature coil, as already referred to. I have stated that a short-circuit voltage of three or four volts per armature turn gave prohibitive designs and that it was necessary practically to double this. This means that the field coils also have six to eight volts per turn generated in them. The total number of field turns must, therefore, be very small in order to keep down the field electromotive force, for this represents simply a choke-coil in series with the armature. If the armature counter electromotive force should be 200 volts, for instance, which is rather high in practice with 25-cycle motors, then a field self-induction of half this value would allow about 14 turns total in the field winding. Compare this with direct-current motors with 150 to 200 field turns for 550 volts, or 60 to 80 turns for 220 volts. The alternating-current 25-cycle motor, therefore, can have only about 20% to 25% as many field turns as the ordinary direct-current motor. This fact makes it particularly hard to design large motors where there must be many poles. In the single-phase motor the induction per pole being limited by the permissible short-circuit voltage, it is necessary to use a large number of poles for heavy torques; but the total number of field turns must remain practically constant on account of the self induction, while in reality the number of turns should be increased as the number of poles is increased. With a given number of poles we may have just sufficient field turns to magnetize the motor up to the required point; but if a large number of poles should be required, then we at once lack field turns and must either reduce the field induction, and thus reduce the output, or must add more field turns and thus get a higher self-induction or choking action in the field, with a consequent reduction in power-factor. Here is where a lower frequency comes in to advantage, for, as I showed before, with the same relative inductive effect, the field turns can be increased directly as the frequency is decreased. The use of 15 cycles thus permits 67% more field turns than 25 cycles and raises our permissible magnetizing limits enormously. This problem is encountered particularly in gearless locomotive motors of large capacity. For increased capacity the driving wheels are made larger, thus permitting a larger diameter of motor, the length, axlewise, being fixed. But with increased diameter of drivers, the number of revolutions is decreased for a given number of miles per hour. With 25-cycle motors we soon encounter the above mentioned limiting condition in field turns; beyond this point the characteristics of the motor must be sacrificed, and even doing this we soon reach prohibitive limits. By dropping the frequency to 15 cycles, for instance, we change the whole situation. The induction per pole can be increased and the number of poles, if desired, can also be increased. The practical result is that, in the case of a high-speed passenger locomotive with gearless motors, a 700-h.p. 15-cycle motor can be got in on the same diameter of drivers as required for a 500-h.p. 25-cycle motor. Also a 500-h.p. 15-cycle motor goes in on the same drivers as a 360-h.p., 25-cycle motor. At the same time these 15-cycle motors have better all round characteristics than the 25-cycle machines as regards efficiency, power-factor, starting, over-load commutation, etc.

Returning to the design of the motor, there is one other electromotive force of self induction which may be considered; namely, that generated in the armature winding and in the opposing winding in the pole face, usually called the neutralizing or compensating winding.

Fig. 4 shows a section of the field and armature corresponding to the usual direct-current motor, or an alternating-current motor without compensating winding. In the direct-current motor the armature ampere-turns lying under the pole face tend to set up a local field around themselves, producing what is known as cross-induction. This produces no harmful effect except in crowding the field induction to one edge of the pole, thus shifting the magnetic field slightly and possibly affecting the commutation in a small degree. But if the armature is carrying alternating current this cross flux will generate an electromotive force in the armature winding, and this will be added to the field self-induction, thus increasing the self-induction or choking action of the machine. As the armature turns on such motors are much greater, in proportion, than the field turns, it is evident that the ampere-turns under the pole face can exert a relatively great cross-magnetizing effect. This high cross-magnetization generates a high armature self-induction which may be almost as much as the field self-induction. Further, this great cross-induction would tend to shift the magnetic field quite appreciably, thus affecting the commutation to some extent.

To overcome this serious objection, the neutralizing winding is added. This is a winding embedded in the pole face and so arranged that it opposes the armature cross-magnetizing action. The arrangement is shown in Fig. 5. As it opposes and thus neutralizes the cross-induction set up by the armature winding, it eliminates the self-induction due to the cross-magnetization. It also prevents shifting of the magnetic field and thus eliminates its injurious effect on commutation. As the cross-flux is practically cut out the armature winding becomes relatively non-inductive. There is, however, a small self-induction in the armature and neutralizing windings, due to the small flux which can be set up in the space between the two windings, they being on separate cores with an air-gap between.

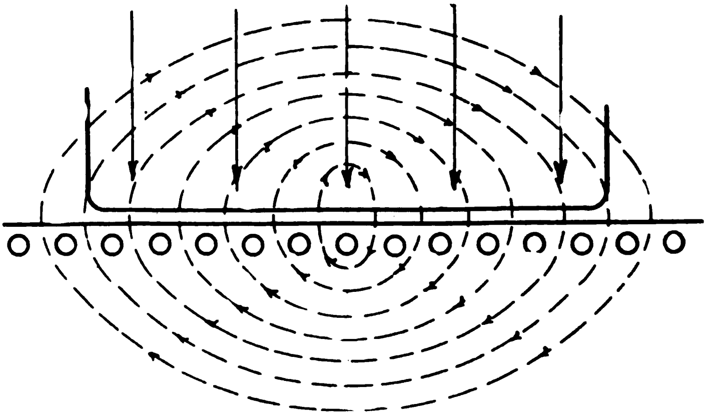

FIG. 4

I have stated that the field turns of the alternating-current motor can be only 20% to 25% as many as in ordinary direct-current practice. It may be questioned how the field can be magnetized with so few field turns. This has been one of the most difficult problems in the motor. Obviously, one solution would be the use of a very small air-gap, but in railway practice there are objections to making the air-gap unduly small. Furthermore, if the armature has large open slots, as shown in Fig. 6, experience shows that a reduction in the clearance between the armature and field iron does not represent a corresponding decrease in the effective length of the air-gap, due to the fact that the fringing of the magnetic flux from the tooth tip of the pole face changes as the air-gap is varied. The most effective construction yet used consists in making the armature slots of the partially closed type as in the secondary of an induction motor. This is shown in Fig. 7.

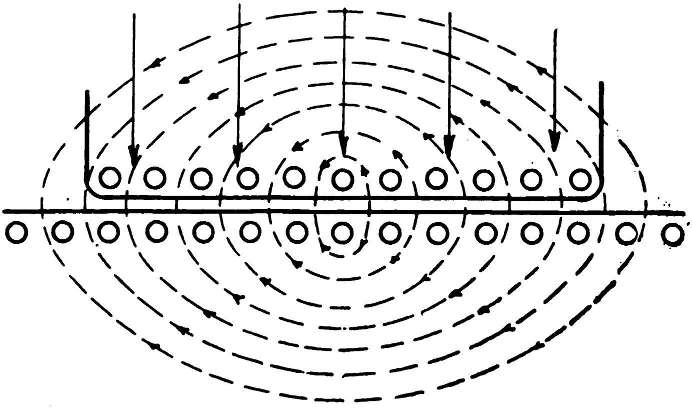

FIG. 5

With this construction practically the whole armature surface under the pole becomes effective, and the true length of air-gap is practically the same as the distance from iron to iron. With the increased effective surface, due to this construction, the length of air-gap need not be unduly decreased, which is of considerable importance in railway work.

A further assistance in reducing the required field turns is the field construction used in the single-phase motor. The magnetic circuit consists of laminations of high permeability and usually without joints across the magnetic path. The iron is also worked either below the bend in the saturation curve or, at most, only slightly up on the bend, except in the case of very low frequency motors where more field turns are permissible.

Taking the whole magnetic circuit into account, on 25-cycle motors about 80% of the whole field excitation is expended in the air-gap, while in direct-current motors, even with a much larger air-gap, as much as 40% to 50% of the magnetization may be expended in the iron and in the joints.

This armature construction with the partly closed slots has been found very effective in large, slow-speed, single-phase motors in which a relatively large number of poles is required. This construction is used on the New Haven 250-h.p., 25-cycle motors; also on the 500 h.p., 15-cycle motor on the Pennsylvania locomotive exhibited at Altantic City at the Street Railway convention, last October. Geared motors for interurban service can be constructed with ordinary open slots with bands, and many have been built that way. The semi-closed slot, however, allows more economical field excitation.

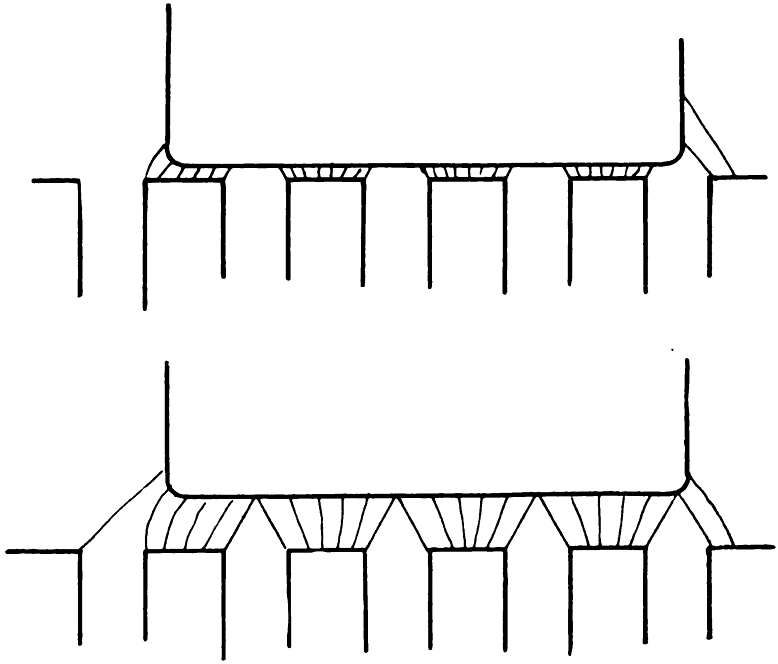

FIG. 6

It may be asked what the objection is to low power-factors on single-phase railway motors, aside from the increased watt-less load on the generating station and transmission circuits. There is an objection to the low power-factor in such motors, a very serious one. This lies in the greatly reduced margin for overload torque in case the supply voltage is lowered. In railway work it is generally the requirement of abnormal loads or torques which causes a reduction in the line voltage; that is, the overload pulls down the trolley voltage just when a good voltage condition is most necessary. This is true of direct current as well as alternating current. In the direct current motor, however, such reduction in voltage simply means reduced speed but in the alternating current motor the effect may be more serious.

To illustrate, assume a motor with a power-factor of 90% at full load. The energy component of the input being 90%, the inductive component is about 44% or, putting it in terms of electromotive force the inductive volts of the motor are 44% of the terminal voltage. Neglecting the resistance of the motor, a supplied electromotive force of 44% of the rated voltage would just drive full-load current through it and develop full-load torque. With full voltage applied the motor could develop from five to six times full-load torque. Under abnormal conditions a drop of 30% in the line voltage would still give sufficient voltage at the motor terminals to develop two and one half to three times full-load torque. Let us next take a motor of 80% power-factor at full load. The inductive voltage would then become 60% of the terminal voltage, and therefore 60% of the rated voltage must be applied to send full-load current

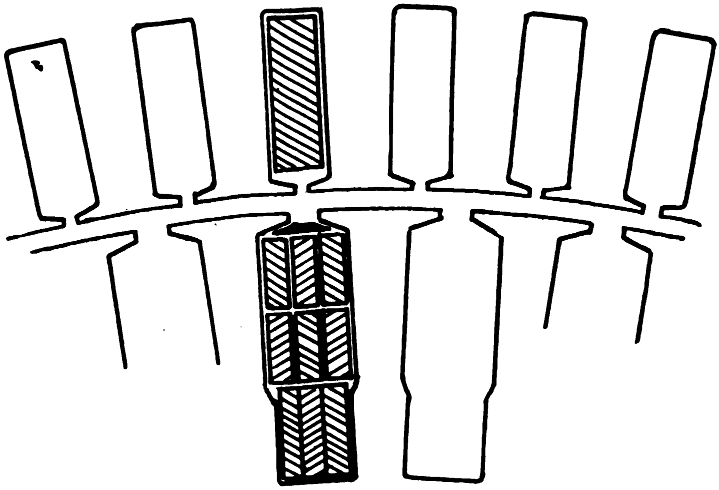

FIG. 7

through the motor. This neglects the resistance of the motor, which, if included, means that slightly more than 60% of the voltage is required. With full voltage applied, this motor would develop about three or four times the rated torque. With 30% drop in the line voltage the motor could develop from one and one half to two times rated torque, which is hardly enough for an emergency condition.

Taking, next, a motor with 70% power-factor at full load it would require 70% of the rated voltage to send full-load current through the motor; with 30% drop in line voltage the motor could just develop full-load torque, and even with 15% drop it would develop only about one and one half times torque. As 15% drop is liable to occur on any ordinary system, this latter motor would be a very unsafe one.

It is evident from the above that it would be bad practice in railway work to install motors with very low full-load power-factors. In general, the higher the power-factor the more satisfactory will be the service, other things being equal.

I have endeavored to explain some of the problems which have been encountered in the design of single-phase commutator railway motors of sizes suitable for all classes of railway service. Here is a type of machine which has been known for a great many years, but which, until the last few years, has been considered utterly bad. In a comparatively short time it has been changed from what was considered an unworkable machine to a highly satisfactory one and this has been accomplished, not by any radically new discoveries, but by the common-sense application of well known principles to overcome the apparently inherent defects of the type. As an indication that the motor is making progress in the railway field, I will mention that the first commercial single-phase railway motors have not been in use more than four or five years, and yet at the present time there have been sold by the various manufacturers in this country and Europe, a total capacity of approximately 200,000 to 250,000 h.p., a very considerable part of which has been put in operation. Considering that the motor was a newcomer in a well established field, the above record is astonishing. However, it may be safely predicted that what has been done in the last five years will hardly make a showing compared with what will be done during the next five years, for the real field for such motors, namely, heavy railway work, has hardly been touched.

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A MINIMUM-WORK METHOD FOR THE SOLUTION OF ALTERNATING CURRENT PROBLEMS

BY HAROLD PENDER

In a single-phase alternating-current circuit, the ratio of the mean effective pressure E to the mean effective current I, is defined as the impedance z of the circuit; that is,

$$z = \frac{E}{I}$$

The power absorbed in the circuit is

$$W = r\, I^2$$

where r is the effective resistance of the circuit.

If L is the coefficient of self-induction of the circuit and $\sim$ the frequency, then the relation between the resistance and impedance of a circuit is

$$z = \sqrt{r^2 + x^2}$$

where x, called the reactance of the circuit, equals $2\,\pi \sim L$.

For two or more circuits *in series*, the resistances and reactances are additive, respectively; the resultant impedance is therefore

$$z = \sqrt{(r_1 + r_2 + \quad . \;\; . \;\; . \quad)^2 + (x_1 + x + \quad . \;\; . \;\; . \quad)^2}$$

In the case of two or more circuits *in parallel*, the quantities

Admittance $\qquad y = \frac{I}{E} = \frac{1}{z}$

Conductance $\qquad g = \frac{W}{E^2} = \frac{r}{r^2 + x^2}$

Susceptance $b = \sqrt{y^2 - g^2} = \frac{x}{r^2 + x^2}$

lend themselves more readily to mathematical analysis, since conductances and susceptances are respectively additive; the resultant admittance is therefore

$$y = \sqrt{(g_1 + g_2 + \ . \ . \ . \ ) + (b_1 + b_2 + \ . \ . \ . \ )^2}$$

These complex forms for impedance and admittance render the formulas for most alternating-current problems exceedingly complicated, and numerical calculations become extremely tedious after the first or second operation.

The following method of treating such problems will be found much simpler. The fundamental idea involved is the use of certain factors; namely, the ratio of the reactance to the resistance, the "reactance-factor" t, and the ratio of the resistance to the impedance, the "power-factor" k, instead of employing the reactance and impedance directly. From the triangle giving the relation between resistance, reactance, and impedance,

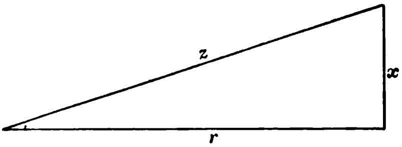

FIG. 1

it is evident that the reactance-factor $t \left(= \frac{x}{r} \right)$ and the power-factor $k \left(= \frac{r}{z} \right)$ are the tangent and cosine, respectively, of the same angle. If either of the two quantities t or k is known, the other can then be taken directly from a table of cosines and tangents. Table I, giving the values of t (tangent) in terms of k (cosine) is arranged in a form more convenient than the usual trigonometric tables. Of the two factors, k is the more readily determined from actual measurements, since

$$k = \frac{W}{E\,I}$$

t can then be taken from the table. If the reactance x and resistance r of the circuit are known, t can be readily calculated, since

$$t = \frac{x}{r}$$

k can then be taken from the table.

Below will be found the solution of a number of alternating-current problems by this new method. A comparison of the formulas deduced with those ordinarily used will make evident at once the simplicity of this method, especially for numerical calculations.

The ordinary quantities, reactance, impedance, conductance, susceptance, and admittance can all be expressed by simple formulas in terms of resistance and the trigonometric quantities t and k, namely:

Resistance $\qquad r = r \qquad$ (1)

Reactance $\qquad x = r\,t \qquad$ (2)

Impedance $\qquad z = \frac{r}{k} \qquad$ (3)

Conductance $\qquad g = \frac{k^2}{r} \qquad$ (4)

Susceptance $\qquad b = g\,t \qquad$ (5)

Admittance $\qquad y = \frac{g}{k} \qquad$ (6)

The relations between current, pressure, and power absorbed in the circuit, are

Current $\qquad I = \frac{k\,E}{r} = \frac{g\,E}{k} = \frac{W}{k\,E} \qquad$ (7)

Pressure $\qquad E = \frac{k\,I}{g} = \frac{r\,I}{k} = \frac{W}{k\,I} \qquad$ (8)

Resistance and conductance may likewise be expressed in terms of current, pressure, and power; namely,

$$r = \frac{W}{I^2} = \frac{(k\,E)^2}{W} \tag{9}$$

$$g = \frac{W}{E^2} = \frac{(k\,I)^2}{W} \tag{10}$$

When $r = 0$, then $g = 0$, and $k = 0$, and the expressions for I and E reduce to the following forms:

Current $$I = bE = \frac{E}{x} \qquad (7a)$$

Pressure $$E = xI = \frac{I}{b} \qquad (8a)$$

The power absorbed in the circuit is, of course, zero.

Reactance-factor of two or more circuits in series. Since resistances and reactances are respectively additive, the combined resistance of two or more circuits is

$$R^* = r_1 + r_2 + \ . \ . \ . \qquad (11)$$

and the combined reactance is

$$X = x_1 + x_2 + \ . \ . \ . \qquad (12)$$

Hence the reactance-factor of two or more circuits in series is

$$T = \frac{X}{R} = \frac{x_1 + x_2 + \ . \ . \ .}{r_1 + r_2 + \ . \ . \ .} \qquad (13)$$

or

$$T = \frac{r_1 t_1 + r_2 t_2 + \ . \ . \ .}{R} \qquad (13a)$$

The resultant reactance-factor has the form of a weighted average, the " weight " being the corresponding resistance.

Reactance-factor of two or more circuits in parallel. Since conductances and susceptances are respectively additive, the combined conductance of two or more circuits is

$$G = g_1 + g_2 + \ . \ . \ . \qquad (14)$$

and the combined susceptance is

$$B = b_1 + b_2 + \ . \ . \ . \qquad (15)$$

and the reactance-factor of the combined circuits is

$$T = \frac{B}{G} = \frac{b_1 + b_2 + \ . \ . \ .}{g_1 + g_2 + \ . \ . \ .} \qquad (16)$$

or

$$T = \frac{g_1 t_1 + g_2 t_2 + \ . \ . \ .}{G} \qquad (16a)$$

---

* Throughout this paper lower-case italic letters will be used for constants of a simple circuit, capitals for the constants of combined circuits.

As in the case of two or more circuits in series the reactance-factor of the combined circuits is a weighted average, the weights for parallel circuits being the corresponding conductances.

SIMPLE TRANSMISSION CIRCUIT

Single-phase line. Consider a [load of W watts, of power-factor k, supplied at a pressure E over a line of resistance r_1 ohms and reactance factor t_1. (Table II gives the values of the reactance factor for various sizes of wires spaced various distances apart.)

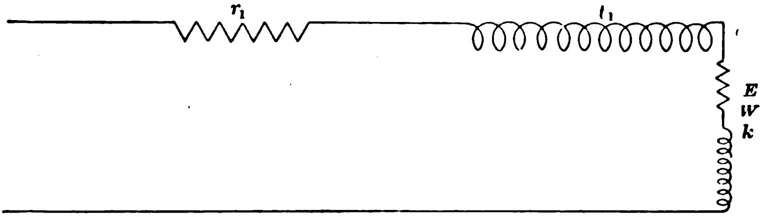

FIG. 2

Given the above constants, to find

I = current, in amperes
E_0 = pressure at generator end, in volts
K_0 = power-factor at generator end
W_0 = power supplied at generator end, in watts.

From equation (7)

$$I = \frac{W}{k\,E}$$

From equation (9), the effective resistance of the receiver is

$$r = \frac{(k\,E)^2}{W}$$

From Table I take the reactance-factor t, corresponding to k.

From equation (13a) the reactance-factor at the generator end is

$$T_0 = \frac{r\,t + r_1\,t_1}{r + r_1}$$

whence K_0, the power-factor at the generator end, is taken directly from Table I.

From equations (8) and (7) the pressure at the generator end is

$$E_0 = \frac{r+r_1}{K_0} I = \frac{r+r_1}{r} \; \frac{k}{K_0} E$$

From equation (9) the power supplied at the generator end is

$$W_0 = (r+r_1) I^2 = \frac{r+r_1}{r} W$$

These formulas can be somewhat simplified by introducing the ratio of power lost in line to power delivered, which can be represented by Q, and has the value

$$Q = \frac{r_1}{r} = \frac{r_1 I}{k E} = \frac{r_1 W}{(k E)^2}$$

Making this substitution and assembling the formulas

Current $$I = \frac{W}{k E}$$

Ratio power lost to power delivered

$$Q = \frac{r_1 I}{k E}$$

Power supplied at generator end

$$W_0 = (1+Q) W$$

Reactance-factor at generator end

$$T_0 = \frac{t+t_1 Q}{1+Q}$$

Power-factor at generator end,

K_0 corresponding to T_0 from Table I

Ratio of pressure drop to pressure delivered

$$D = \frac{k}{K_0} (1+Q) - 1$$

Pressure at generator end

$$E_0 = (1+D) E$$

17

Three-phase line. The formulas just deduced also hold for a three-phase line except that I, the line current, is

$$I = \frac{W}{\sqrt{3}\,k\,E}$$

and the resistance r_1 is the resistance of *each leg* of the line.

The formula for generator pressure E_0 can be put in a form not involving the calculation of the power-factor K_0, which form also leads to a very simple approximate expression for the pressure-drop in the line. Remembering the trigonometric relations between T and K, we have

$$\frac{1}{K_0} = \sqrt{1+T_0^2} \quad (\text{since } \sec^2 = 1+\tan^2)$$

Making this substitution in the above expression for E_0 we get

$$E_0 = E\sqrt{1+2\,(1+t_1\,t)\,k^2\,Q+\left(\frac{k}{k_1}\,Q\right)^2}$$

Expanding this radical in the form of an infinite series and neglecting the terms of the second or higher order in Q, we have as a first approximation, for ordinary practical cases where the power lost in the line is 20 per cent. or less and the reactance of the line of the same order of magnitude as the resistance,

$$E_0 = E\,[1+(1+t_1\,t)\,k^2\,Q]$$

or putting

$$M = (1+t_1\,t)k^2$$

$$E_0 = (1+M\,Q)\,E$$

The ratio of pressure lost in the line to pressure at receiver is then

$$D = M\,Q^*$$

M may be called the " drop-factor ", it depends only on the reactance-factors of the line and the load.

The power-factor at the generator is

$$K_0 = \frac{W_0}{E_0\,I} = \frac{1+Q}{1+D}\,k$$

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* For a geometric proof of this formula see an article by the author in the *Elec. World*, Vol. 46, p. 18, 1905.

We have then for the three characteristics of a transmission line the simple formulas

$$\left.\begin{array}{ll}\text{Ratio of power lost to power delivered} & Q=\dfrac{r_1 W}{(k E)^2}\\ \text{Ratio of pressure lost to pressure delivered} & D=M\,Q\\ \text{Power factor at generator end} & K_0=\dfrac{1+Q}{1+D}\,k\end{array}\right\}\quad(18)$$

The expressions for D and K_0 are approximate, but for most practical cases are sufficiently accurate. Table III gives the values of M for various load power-factors and line reactance-factors. The degree of approximation involved in the use of this table is also indicated; note that an error of five per cent., for example, in a pressure drop of ten per cent. produces an error of only 0.5 per cent. in the absolute value of the pressure.

Three-phase line. These formulas also hold for a three-phase line when r_1 represents the resistance of *each leg* of the line.

Numerical examples. A load of 5000 kw. is to be delivered at 30,000 volts to a receiver having a 95 per cent. power-factor over a 40-mile single-phase line of No. 00 copper wire; frequency 25 cycles, wires 4 ft. apart.

From Table II, the resistance of the line is

$$r = 2\times 40\times 0.411 = 32.9$$

and the reactance-factor

$$t_1 = \frac{2.87}{4} = 0.717$$

Applying the exact formulas (17):

Current $$I=\frac{5\times 10^6}{0.95\times 3\times 10^4}=175.6 \text{ amperes.}$$

Ratio of power lost to power delivered

$$Q=\frac{32.9\times 175.6}{0.95\times 3\times 10^4}=0.203$$

Power supplied at generator end

$$W_0=1.203\times 5000=6020 \text{ kw.}$$

Reactance-factor at generator end

$$T_0 = \frac{0.329 + 0.717 \times 0.203}{1.203} = 0.394$$

Power-factor at generator end $K_0 = 0.930$

Ratio of pressure drop to pressure delivered

$$D = \frac{0.95}{0.93} \times 1.203 - 1 = 0.230$$

Pressure at generator end $E_0 = 1.230 \times 30{,}000 = 36{,}900$ volts.

Applying the approximate formulas (18)
Ratio of power loss to power delivered

$$Q = \frac{32.9 \times 5 \times 10^6}{(0.95 \times 3 \times 10^4)^2} = 0.203$$

Drop-factor $M = 1.14$ from Table III.

Ratio of pressure drop to pressure delivered

$$D = 1.14 \times 0.203 = 0.232$$

Power-factor at generator end

$$K_0 = \frac{1.203}{1.232} \times 0.95 = 0.928$$

The value for D is 1 per cent. high, and the value for K_0 0.2 per cent. low.

Consider the same load supplied over a *three-phase line* of the same length; the power-factor, frequency, size, and spacing of the wires remaining the same.

In this case
Resistance of each leg $r_1 = 40 \times 0.411 = 16.4$

Reactance-factor $t_1 = \frac{2.87}{4} = 0.717$

Applying the exact formulas (17)

Current $I = \frac{5 \times 10^6}{\sqrt{3}.95 \times 3 \times 10^4} = 101.5$ amperes.

Ratio of power lost to power delivered

$$Q=\frac{16.4\times5\times10^6}{(0.95\times3\times10^4)^2}=0.101$$

Power supplied at generator end

$$W_0=1.101\times5000=5505 \text{ kw.}$$

Reactance-factor at generator end

$$T_0=\frac{0.329+0.717\times0.101}{1.101}=0.364$$

Power-factor at generator end

$$K_0=0.940$$

Ratio of pressure drop to pressure delivered

$$D=1-\frac{0.95}{0.94}\times1.101=0.113$$

Pressure at generator end $E_0=1.113\times30{,}000=33{,}600$ volts

Applying the approximate formula (18)

$$Q=\frac{16.4\times5\times10^6}{(0.95\times3\times10^4)^2}=0.101$$

$$M=1.14$$

Ratio of pressure drop to pressure delivered

$$D=1.14\times0.101=0.115$$

Power-factor at generator end

$$K_0=\frac{1.101}{1.115}\times0.95=0.938$$

THE CAPACITY EFFECT IN A TRANSMISSION LINE

The capacity effect in a transmission line can be calculated with sufficient accuracy in most practical cases by considering a condenser of one-half the capacity of the line shunted across the line at each end, or as shown diagrammatically, where, in case of a *single-phase line*

r_1 = resistance of both wires in ohms
t_1 = reactance factor of the line

b = one half the capacity susceptance of the line (see Table IV)
E = pressure between wires at receiver in volts
W = power delivered in watts
k = power-factor of the load

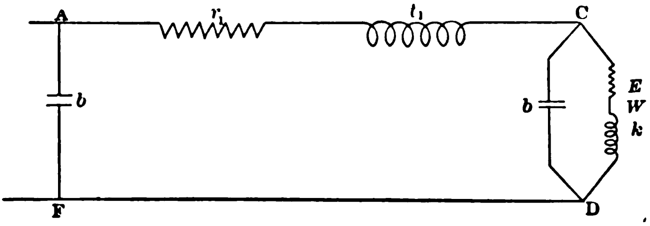

FIG. 3

Then,
Conductance of the receiver (equation 10)

$$g = \frac{W}{E^2}$$

Reactance-factor of receiver: t corresponding to k
Reactance factor of the load and the condenser in parallel at receiver end (equation 16a)

$$T_1 = \frac{g\,t + b}{g}$$

whence from equation (10)

$$T_1 = t + \frac{b\,E^2}{W} \tag{19}$$

Power factor of the load and the condenser in parallel at receiver end: K_1 corresponding to T_1

When K_1 has been found, the power loss, regulation, and power factor of the circuit A C D can be determined either by the exact formulas 17 or the approximate formula 18. The power loss and regulation of the complete circuit A C D F is the same as for the circuit A C D; the power-factor of the circuit A C D F, that is, the power-factor at the generator end, is the power-factor corresponding to the reactance factor of the complete circuit, *i. e.*,

$$T_0' = T_0 + \frac{b\,E_0^2}{W_0} \tag{20}$$

where T_0 is the reactance-factor of the circuit A C D.

Three-phase line. The above equations also hold for a three-phase line when

r_1 = resistance of each wire in ohms
b = capacity susceptance of each pair of wires

the other symbols having the same meaning as in the case of a single-phase line.

Example: A load of 7500 kw. is to be delivered at 60,000 volts to a receiver having a 90 per cent. power-factor over a three-phase line of No. 00 hemp-cored copper cable (diameter 0.45 in.), 140 miles long; frequency 60 cycles, wires spaced 8 ft. apart.

From the data given:

Resistance of each wire in ohms, $r_1 = 140 \times 0.411 = 57.5$ (Table II)

Reactance-factor $t_1 = 0.6 \times 3.2 = 1.92$ (Table II)

Capacity susceptance of each pair of wires

$b = -0.6 \times 4.64 \times 10^{-6} \times 140 = -0.00039$ (Table IV)

Pressure between wires at receiver $E = 6 \times 10^4$

Power delivered $W = 7.5 \times 10^6$

Power-factor of load $k = 0.9$

Then from equation 19,

$$T_1 = 0.484 - \frac{0.00039 \times (6 \times 10^4)^2}{7.5 \times 10^6} = 0.297$$

Using the approximate formula 18,

$$K_1 = 0.959$$

Ratio of power lost to power delivered

$$Q = \frac{57.5 \times 7.5 \times 10^6}{(0.959 \times 6 \times 10^4)^2} = 0.130$$

Drop-factor, $M_1 = (1 + 1.92 \times 0.297)\ (0.959)^2 = 1.44$

Ratio of pressure lost to pressure delivered

$$D = 1.44 \times 0.130 = 0.187$$

Total power supplied by generator

$$W_0 = 1.13 \times 7{,}500 = 8{,}470 \text{ kw.}$$

Pressure at generator $E_0 = 1.187 \times 60{,}000 = 71{,}200$ volts

Power-factor of circuit A C D

$$K_0 = \frac{1.13}{1.187} \times 0.959 = 0.913$$

Reactance-factor of circuit A C D

$$T_0 = 0.448$$

Reactance-factor of complete circuit (equation 20)

$$T_0' = 0.448 - \frac{0.00039 \times (71{,}200)^2}{8.47 \times 10^6} = 0.204$$

Power-factor of complete circuit A C D F

$$K_0 = 0.98$$

The Alternating-current Transformer

In treating the transformer it is simpler to reduce all the constants of the secondary to equivalent primary values; that is, to consider a transformer having a one-to-one ratio. If the actual ratio of the primary turns to secondary turns is a, then the true secondary resistance and reactance are each multiplied by a^2, the true secondary electromotive force is multiplied by a, and the true secondary current divided by a. The transformer may then be represented diagrammatically as shown where

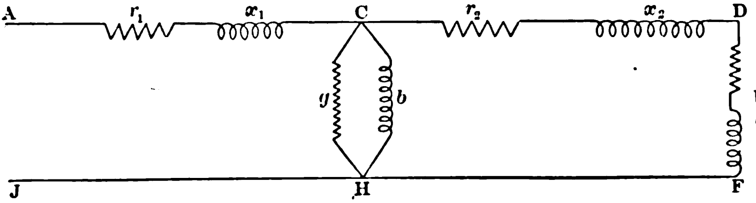

Fig. 4

r_1 = primary resistance in ohms
x_1 = primary reactance in ohms
r_2 = secondary resistance, reduced to primary, in ohms
x_2 = secondary reactance, reduced to primary, in ohms
g = primary exciting conductance
b = primary exciting susceptance

E = secondary terminal electromotive force, reduced to primary
W = external load on secondary
k = power-factor of the external load

The following is the complete solution:

Receiver-circuit D F

Resistance	$r = \frac{(k\,E)^2}{W}$	(from equation 9)
Reactance-factor	t corresponding to k	

Receiver in series with secondary-circuit C D F

Resistance	$R_2 = r + r_2$	(from equation 11)
Reactance-factor	$T_2 = \frac{r\,t + x_2}{R_2}$	(from equation 13)
Conductance	$G_2 = \frac{K^2}{R_2}$	(from equation 4)

Receiver in series with secondary shunted by exciting circuit—circuits C D F and C H F in parallel.

Conductance	$G = G_2 + g$	(from equation 14)
Reactance-factor	$T = \frac{G_2\,T_2 + b}{G}$	(from equation 16)
Resistance	$R = \frac{K^2}{G}$	(from equation 4)

Complete-circuit—A C in series with C D F and C H F in parallel

Resistance	$R_1 = R + r_1$	(from equation 11)
Reactance-factor	$T_1 = \frac{R\,T + x_1}{R_1}$	(from equation 13)
Then power-factor	K_1 corresponding to T_1	
Receiver current	$I_2 = \frac{W}{k\,E}$	(from equation 7)

Induced electromotive force (pressure across D F)

$$E' = \frac{R_2 I_2}{K_2} \qquad \text{(from equation 8)}$$

Magnetizing current $I_m' = b\,E'$ (from equation 7a)

Total exciting current $I' = \frac{g\,E'}{k'}$ (from equation 7)

where k' corresponds to the reactance factor $t' = \frac{b}{g}$

Total primary current $I_1 = \frac{G\,E'}{K}$ (from equation 7)

Primary impressed electromotive force

$$E_1 = \frac{R_1 I_1}{K_1} \qquad \text{(from equation 8)}$$

Total power input $W_1 = R_1\,I_1^2$ (from equation 9)

Power factor of total input is K_1 corresponding to T_1

Efficiency $e = \frac{W_2}{W_1}$

Since the exciting current of a transformer is small compared with the full-load current, and is practically in quadrature therewith, the regulation may be determined with sufficient accuracy by neglecting the exciting current altogether, in which case the transformer diagram reduces to that of the simple transmission line, and equations (17) or (18) are directly applicable.

Example. Given a transformer of the following constants

Ratio of primary to secondary turns	$a = 10$
Primary resistance	$r' = 5$
Primary reactance	$x' = 11$
Actual secondary resistance	$r'' = 0.04$
Actual secondary reactance	$x'' = 0.09$

Exciting current negligible.

To find regulation D when the secondary is supplying 5000 kw. at 10,000 volts to a receiver of 85 per cent. power-factor.

Total equivalent resistance $r_0 = r' + a^2\, r'' = 5 + 100 \times .04 = 9$
Total equivalent reactance $x_0 = x' + a^2\, x'' = 11 + 100 \times .09 = 20$

Equivalent reactance factor $t_0 = \dfrac{20}{9} = 2.22$

Applying equations (18)

Ratio of copper loss to power delivered

$$Q = \frac{9 \times 5 \times 10^6}{(0.85 \times 6 \times 10^4)^2} = 0.0173$$

Drop-factor $M = 1.71$ (from Table II)

Regulation $D = 1.71 \times 0.0173 = 0.0296$

The total power loss in the transformer is $Q\, W +$ the core loss.

The equivalent resistance and reactance factor of a transformer is readily obtained from the short circuit test.

Let

I_0 = primary current when secondary is short circuited

E_0 = primary applied pressure when secondary is short circuited, small compared to normal pressure

W_0 = input in watts

Then

Equivalent resistance $r_0 = \dfrac{W_0}{I^2_0}$

Power-factor $k_0 = \dfrac{W_0}{E_0 I_0}$

Reactance-factor t_0 corresponding to k_0

Transformer in Series with a Transmission Line

A transmission line and transformer in series reduce to a simple transmission circuit having a resistance equal to the sum of the line and transformer resistances and a reactance equal to the sum of the line and transformer reactances. The effect of the exciting current on the copper loss and pressure drop may be neglected. In figuring the total efficiency the core loss of the transformer must of course be included.

THE INDUCTION MOTOR

The current taken by an induction motor running at slip s is the same as the motor would take if the secondary were locked and the secondary resistance increased from r_2 to r_2/s and the secondary reactance increased from $s\,x_2$ to x_2 respectively; in other words the performance of an induction motor is the same as that of a transformer with a variable resistance in the secondary. Diagrammatically each phase of the motor may be represented as shown:

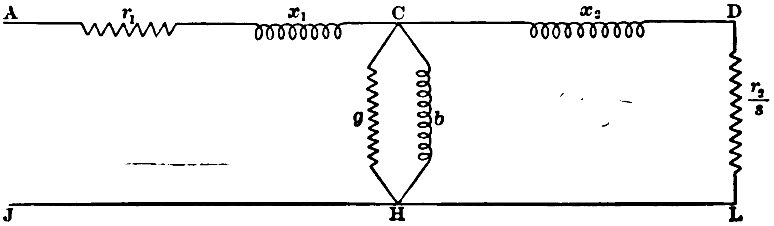

FIG. 5

where r_1 = primary resistance per phase
x_1 = primary reactance per phase
r_2 = secondary resistance per phase reduced to the primary.
x_2 = secondary reactance per phase reduced to the primary.
g = exciting admittance per phase
b = exciting susceptance per phase
s = slip
F = total loss in windage and friction at synchronous speed
$(1-s)F$ = total loss in friction and windage when speed = $n\,(1-s)$
E = impressed volts per phase (equals volts between terminals for a delta connected primary; for star connected primary equals volts between terminals divided by $\sqrt{3}$)

Also let
q = number of phases
n = synchronous speed in revolutions per minute

Then *for the secondary circuit C D L*

Resistance $R_2 = \frac{r_2}{s}$

Reactance-factor $T_2 = \frac{x}{R_2}$

Conductance $G_2 = \frac{R_2^2}{R_2}$

Secondary in parallel with exciting circuit, circuits $< \frac{\text{CDLH}}{\text{CH}} >$

Conductance $G = G_2 + g$

Reactance-factor $T = \frac{G_2\, T_2 + b}{G}$

Resistance $R = \frac{R^2}{G}$

Complete circuit

Resistance $R_1 = R + r_1$

Reactance-factor $T_1 = \frac{R\,T + x_1}{R_1}$

Then

Primary current $I_1 = \frac{K_1\, E_1}{R}$

Induced electromotive force

$$E' = \frac{K\, I_1}{G}$$

Exciting current $I' = \frac{g\, E'}{k'}$

where k' corresponds to $t' = \frac{b}{g}$

Secondary current $I_2 = \frac{G_2\, E'}{K^2}$

Total watts supplied to primary $W_1 = q\, R_1\, I_1^2$
Total watts supplied to secondary $W_2' = q\, R_2\, I_2^2$
Watts lost in true secondary resistance $= q\, r_2\, I_2^2$
Mechanical output of motor $W_2 = (1-s)\,[q\, R_2\, I_2^2 - F]$

Torque in pounds at one-foot radius

$$T = \frac{7.04\ W_2}{n(1-s)}$$

Efficiency $$e = \frac{W_2}{W_1}$$

Power-factor K_1 corresponding to T_1

This is the complete solution of the induction motor, but by making one or two assumptions not strictly true, but sufficiently accurate for most practical purposes, a somewhat simpler set of formulas can be obtained

In the first place the total reactance of the motor can be considered in the primary; secondly, the core loss, friction, and windage can be lumped under one head, the " equivalent conductance per phase "; secondly, the total reactance can be considered as in the primary. The diagram for the induction motor then becomes

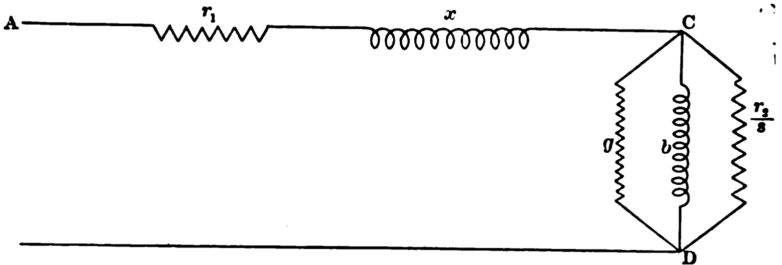

FIG. 6

where r_1 = primary resistance per phase
x = total reactance (primary and secondary) per phase
r_2 = secondary resistance per phase
g = equivalent exciting conductance per phase
b = exciting susceptance per phase
s = slip
E = impressed volts per phase (equals volts between terminals for a delta connected primary; for a star connected primary equals volts between terminals divided by $\sqrt{3}$)

Then equivalent conductance of secondary

$$G_2 = \frac{s}{r_2}$$

For the multiple circuit C D

Conductance $G = G_2 + g$

Reactance-factor $T = \frac{b}{G}$

Resistance $R = \frac{R^2}{G}$

Complete circuit A C D

Resistance $R_1 = R + r_1$

Reactance-factor $T_1 = \frac{R\ T + x}{R_1}$

Then

Primary current $I_1 = \frac{K_1\ E_1}{R_1}$

Secondary current $I_2 = \frac{G_2\ R\ I}{K}$

Primary input $W_1 = q\ R_1\ I^2$

Mechanical output $W_2 = \frac{(1-s)\ q\ I_2^2}{G_2}$

Torque in pounds at one-foot radius

$$T = \frac{7.04}{n\ (1-s)}\ W_2$$

Efficiency $e = \frac{W_2}{W_1}$

Power-factor K_1 corresponding to T_1

Example. Given a three-phase induction motor star-connected, 550 volts between terminals, 375 rev. per min., having the following constants

Primary resistance per phase	r_1	$= 0.027$	ohms
Total reactance per phase	x	$= 0.25$	"
Secondary resistance per phase	r_2	$= 0.022$	"
Equivalent exciting conductance per phase	g	$= 0.024$	"
Exciting susceptance per phase	b	$= 0.36$	"
Revolutions per minute	n	$= 375$	"

What will be the performance of the motor when the slip $s = 0.03$?

Since the primary is star connected

$$E = \frac{550}{\sqrt{3}} = 318$$

Substituting these values in the formulas just deduced

$$G_2 = \frac{0.03}{0.022} = 1.364$$

$$G = 1.364 + 0.024. = 1.388$$

$$T = \frac{0.36}{1.388} = 0.259$$

$$K = 0.968$$

$$R = \frac{(0.968)^2}{1.388} = 0.675$$

$$R_1 = 0.675 + 0.027 = 0.702$$

$$T_1 = 0.605$$

Power factor of motor $K_1 = 0.856$

Primary current $I_1 = \frac{0.856 \times 318}{.702} = 388$ amperes

Secondary current $I_2 = \frac{1.364 \times 0.675 \times 338}{0.968} = 369$ amperes

Primary input $W_1 = 3 \times 0.702 \times 388^2 = 316$ kw.

Mechanical output $W_2 = \frac{0.97 \times 3 \times 369^2}{1.364} = 291$ kw.

Torque $T = \frac{7.04 \times 291000}{375 \times 0.97} = 5630$ lb.

Efficiency $e = \frac{291}{316} = 0.921$

The constants of an induction motor are easily determined from the free running and locked tests.

Let
E' = primary impressed volts per phase when running light
W' = watts input per phase when running light
I' = current per phase, when running light
E_0 = primary impressed volts per phase, rotor locked
W_0 = watts input per phase, rotor locked
I_0 = current input per phase, rotor locked
Primary resistance per phase r_1 measured by means of direct current

Then

Secondary resistance per phase $r_2 = \frac{W_0}{I_0^2} - r_1$

Power-factor locked $k_0 = \frac{W_0}{E_0 I_0}$

Total reactance per phase $x = (r_1 + r_2)\ t_0$
where t_0 corresponds to k_0

Equivalent exciting conductance per phase $g' = \frac{W'}{E'^2}$

Power-factor, running light $k' = \frac{W'}{E' I'}$

Exciting susceptance per phase $b' = g'\ t'$
where t' corresponds to k'

TABLE 1.

VALUES OF t (= tan) IN TERMS OF k (=cos).

K	0.000	0.002	0.004	0.006	0.008	K	0.000	0.002	0.004	0.006	0.008
0.00		500	250	167	125	0.50	1.732	1.723	1.714	1.705	1.696
0.01	100	83.3	71.4	62.5	55.5	0.51	1.687	1.678	1.669	1.660	1.651
0.02	50.0	45.4	41.6	38.4	35.7	0.52	1.643	1.634	1.626	1.617	1.608
0.03	33.3	31.2	29.4	27.7	26.3	0.53	1.600	1.592	1.583	1.575	1.567
0.04	24.9	23.8	22.7	21.7	20.8	0.54	1.559	1.550	1.542	1.534	1.526
0.05	20.0	19.2	18.5	17.8	17.2	0.55	1.519	1.511	1.503	1.495	1.487
0.06	16.6	16.1	15.6	15.1	14.7	0.56	1.479	1.471	1.464	1.457	1.449
0.07	14.3	13.8	13.5	13.1	12.8	0.57	1.442	1.434	1.427	1.419	1.412
0.08	12.5	12.2	11.9	11.6	11.3	0.58	1.404	1.397	1.390	1.383	1.376
0.09	11.1	10.8	10.6	10.4	10.2	0.59	1.368	1.361	1.354	1.347	1.340
0.10	9.95	9.75	9.56	9.38	9.21	0.60	1.333	1.326	1.319	1.313	1.306
0.11	9.03	8.87	8.71	8.56	8.41	0.61	1.299	1.292	1.286	1.279	1.272
0.12	8.27	8.14	8.00	7.87	7.75	0.62	1.265	1.259	1.252	1.246	1.239
0.13	7.63	7.51	7.40	7.28	7.18	0.63	1.233	1.226	1.220	1.213	1.207
0.14	7.07	6.97	6.87	6.78	6.68	0.64	1.201	1.194	1.188	1.181	1.175
0.15	6.59	6.50	6.42	6.33	6.25	0.65	1.169	1.163	1.157	1.151	1.144
0.16	6.17	6.09	6.02	5.94	5.87	0.66	1.138	1.132	1.126	1.120	1.114
0.17	5.80	5.73	5.66	5.59	5.53	0.67	1.108	1.102	1.096	1.090	1.084
0.18	5.47	5.40	5.34	5.28	5.22	0.68	1.078	1.072	1.067	1.061	1.055
0.19	5.17	5.11	5.06	5.00	4.95	0.69	1.049	1.043	1.037	1.032	1.026
0.20	4.90	4.85	4.80	4.75	4.70	0.70	1.020	1.015	1.009	1.003	0.997
0.21	4.66	4.61	4.56	4.52	4.48	0.71	0.992	0.986	0.981	0.975	0.969
0.22	4.43	4.39	4.35	4.31	4.27	0.72	0.964	0.968	0.953	0.947	0.942
0.23	4.23	4.19	4.15	4.12	4.08	0.73	0.936	0.931	0.925	0.920	0.914
0.24	4.05	4.01	3.97	3.94	3.91	0.74	0.909	0.904	0.898	0.893	0.887
0.25	3.87	3.84	3.81	3.78	3.75	0.75	0.882	0.877	0.871	0.866	0.860
0.26	3.71	3.68	3.65	3.62	3.59	0.76	0.855	0.850	0.845	0.839	0.834
0.27	3.57	3.54	3.51	3.48	3.46	0.77	0.829	0.823	0.818	0.813	0.808
0.28	3.43	3.40	3.38	3.35	3.33	0.78	0.802	0.797	0.792	0.787	0.781
0.29	3.30	3.28	3.25	3.23	3.20	0.79	0.776	0.771	0.766	0.760	0.755
0.30	3.18	3.16	3.13	3.11	3.09	0.80	0.750	0.745	0.740	0.734	0.729
0.31	3.07	3.05	3.02	3.00	2.98	0.81	0.724	0.719	0.714	0.708	0.703
0.32	2.96	2.94	2.92	2.90	2.88	0.82	0.698	0.693	0.688	0.682	0.677
0.33	2.86	2.84	2.82	2.80	2.78	0.83	0.672	0.667	0.662	0.656	0.651
0.34	2.77	2.75	2.73	2.71	2.69	0.84	0.646	0.641	0.635	0.630	0.625
0.35	2.68	2.66	2.64	2.63	2.61	0.85	0.620	0.614	0.609	0.604	0.599
0.36	2.59	2.58	2.56	2.54	2.53	0.86	0.593	0.588	0.583	0.577	0.572
0.37	2.51	2.50	2.48	2.46	2.45	0.87	0.567	0.561	0.556	0.551	0.545
0.38	2.43	2.42	2.40	2.39	2.38	0.88	0.540	0.534	0.529	0.523	0.518
0.39	2.36	2.35	2.33	2.32	2.30	0.89	0.512	0.507	0.501	0.496	0.490
0.40	2.29	2.28	2.26	2.25	2.24	0.90	0.489	0.479	0.473	0.467	0.461
0.41	2.22	2.21	2.20	2.19	2.17	0.91	0.456	0.450	0.444	0.438	0.432
0.42	2.16	2.15	2.14	2.12	2.11	0.92	0.426	0.420	0.414	0.408	0.401
0.43	2.10	2.09	2.08	2.06	2.05	0.93	0.395	0.389	0.383	0.376	0.370
0.44	2.04	2.03	2.02	2.01	2.00	0.94	0.363	0.356	0.350	0.343	0.336
0.45	1.98	1.97	1.96	1.95	1.94	0.95	0.329	0.321	0.314	0.307	0.299
0.46	1.93	1.92	1.91	1.90	1.89	0.96	0.292	0.284	0.276	0.268	0.259
0.47	1.88	1.87	1.86	1.85	1.84	0.97	0.251	0.242	0.232	0.223	0.213
0.48	1.83	1.82	1.81	1.80	1.79	0.98	0.203	0.192	0.181	0.169	0.156
0.49	1.78	1.77	1.76	1.75	1.74	0.99	0.143	0.127	0.110	0.090	0.063

NOTE: This table is to be used like a table of logarithms, *e. g.*, the reactance factor corresponding to the power-factor k=0.810 is t=0.708.

TABLE 11.

CROSS-SECTION, RESISTANCE AND REACTANCE-FACTORS.

Temperature 20° cent.

Reactance-factors are directly proportional to frequency and to conductivity:

For copper wire and
25 cycles divide the reactance-factors given below by 4.
60 cycles multiply reactance-factors given below by 0.6

For aluminum wire and
25 cycles multiply the reactance-factors given below by 0.155.
60 cycles multiply the reactance-factor given below by 0.372.

No. B. & S.	Cross-section circular mils.	Ohms per mile at 20° cent. or 68° *fahr.*		Reactance-factors for 100 per cent. conductivity and 100 cycles per second							
				Distance apart of wires in feet.							
		Copper	Aluminum	1	2	3	4	5	6	7	8
	500,000	0.109	0.176	6.96	8.24	8.99	9.52	9.93	10.26	10.55	10.80
	450,000	0.121	0.196	6.35	7.50	8.17	8.65	9.02	9.32	9.58	9.80
	400,000	0.137	0.221	5.73	6.75	7.35	7.77	8.11	8.37	8.61	8.80
	350,000	0.156	0.252	5.10	6.00	6.52	6.89	7.18	7.41	7.62	7.79
	300,000	0.182	0.294	4.46	5.22	5.67	5.99	6.24	6.44	6.61	6.76
	250,000	0.218	0.352	3.80	4.44	4.81	5.08	5.28	5.45	5.60	5.72
0000	212,000	0.258	0.417	3.28	3.82	4.14	4.37	4.54	4.68	4.80	4.91
000	168,000	0.326	0.525	2.68	3.11	3.35	3.53	3.67	3.78	3.88	3.96
00	133,000	0.411	0.662	2.18	2.52	2.72	2.86	2.97	3.06	3.13	3.20
0	106,000	0.518	0.835	1.77	2.04	2.20	2.31	2.40	2.47	2.53	2.58
1	83,700	0.653	1.05	1.44	1.66	1.78	1.87	1.94	2.00	2.04	2.08
2	66,300	0.824	1.33	1.17	1.34	1.44	1.51	1.57	1.61	1.65	1.68
3	52,600	1.04	1.68	0.95	1.09	1.16	1.22	1.26	1.30	1.33	1.36
4	41,700	1.31	2.11	0.77	0.88	0.94	0.99	1.02	1.05	1.07	1.09
5	33,100	1.65	2.66	0.63	0.71	0.76	0.80	0.82	0.85	0.87	0.88
6	26,300	2.08	3.36	0.51	0.58	0.61	0.64	0.66	0.68	0.70	0.71

NOTE: The above reactance-factors are calculated for solid wire; they are also correct within about one per cent for an ordinary stranded cable or cable with hemp core having the same cross-sectional area of conductor.

TABLE III.

VALUES OF DROP-FACTOR $M = (1+t_1 t) k^2$

Reactance-factor	Power-factor Lagging.						
	100	98	95	90	85	80	70
0.0	1.00	0.96	0.90	0.81	0.72	0.64	0.49
0.1	1.00	0.98	0.93	0.85	0.77	9.69	0.54
0.2	1.00	1.00	0.96	0.89	0.81	0.74	0.59
0.3	1.00	1.02	0.99	0.93	0.86	0.78	0.64
0.4	1.00	1.04	1.02	0.97	0.90	0.83	0.69
0.5	1.00	1.06	1.05	1.01	0.95	0.88	0.74
0.6	1.00	1.08	1.08	1.05	0.99	0.93	0.79
0.7	1.00	1.10	1.11	1.09	1.04	0.98	0.84
0.8	1.00a	1.12	1.14	1.13	1.08	1.02	0.89
0.9	1.00	1.14	1.17	1.17	1.13	1.07	0.94
1.0	1.00	1.16	1.20	1.21	1.17	1.12	0.99
1.1	1.00b	1.17a	1.23	1.25	1.22	1.17	1.04
1.2	1.00	1.19	1.26	1.29	1.26	1.22	1.09
1.3	1.00	1.21	1.29	1.32	1.30	1.28	1.14
1.4	1.00	1.23	1.32a	1.36	1.35	1.31	1.19
1.5	1.00c	1.25b	1.35	1.40	1.39	1.36	1.24
1.6	1.00	1.27	1.38	1.44a	1.44	1.41	1.29
1.7	1.00	1.29	1.41	1.48	1.48	1.46	1.34
1.8	1.00	1.31	1.44	1.52	1.53	1.50	1.39
1.9	1.00	1.33	1.47b	1.56	1.57	1.55	1.44
2.0	1.00	1.35c	1.50	1.60	1.62	1.60	1.49
2.1	1.00	1.37	1.53	1.64	1.66a	1.65	1.54
2.2	1.00	1.39	1.56	1.68	1.71	1.70	1.59
2.3	1.00	1.41	1.59	1.72b	1.75	1.74	1.64
2.4	1.00	1.43	1.62c	1.76	1.80	1.79	1.69
2.5	1.00	1.45	1.64	1.80	1.84	1.84a	1.74
2.6	1.00	1.47	1.67	1.84	1.89	1.89	1.79
2.7	1.00	1.49	1.70	1.88	1.93	1.94	1.84
2.8	1.00	1.51	1.73	1.92	1.98	1.98	1.89
2.9	1.00	1.53	1.76	1.96	2.02b	2.03	1.94
3.0	1.00	1.55	1.79	2.00	2.07	2.08	1.99
3.1	1.00	1.56	1.82	2.04c	2.11	2.13	2.04
3.2	1.00	1.58	1.85	2.08	2.16	2.18	2.09
3.3	1.00	1.60	1.88	2.12	2.20	2.22	2.14
3.4	1.00	1.62	1.91	2.16	2.25	2.27b	2.19
3.5	1.00	1.64	1.94	2.20	2.29	2.32	2.24
3.6	1.00	1.66	1.97	2.24	2.34	2.37	2.29
3.7	1.00	1.68	2.00	2.28	2.38	2.42	2.34
3.8	1.00	1.70	2.03	2.32	2.42	2.46	2.39
3.9	1.00	1.72	2.06	2.35	2.47c	2.51c	2.44c

a. Above this point the error in P is less than 5% when $Q \overset{=}{<} 0.20$.

b. Above this point the error in P is less than 5% when $Q \overset{=}{<} 0.10$.

c. Above this point the error in P is less than 5% when $Q \overset{=}{<} 0.05$.

TABLE IV.

CAPACITY SUSCEPTANCE PER MILE OF TWO PARALLEL WIRES. FREQUENCY 100 CYCLES PER SECOND.

Capacity susceptance is directly proportional to frequency. For 25 cycles divide the numbers given below by 4; for 60 cycles multiply by 0.6

Size CM B.&S.	Diam. in Inch	Distance apart of wires in feet. 1	2	3	4	5	6	7	8
500,000	0.707	-7.97x10^{-4}	-6.66x10^{-4}	-6.08x10^{-4}	-5.72x10^{-4}	-5.47x10^{-4}	-5.28x10^{-4}	-5.14x10^{-4}	-5.01x10^{-4}
450,000	0.670	-7.85	-6.58	-6.01	-5.66	-5.42	-5.23	-5.09	-4.97
400,000	0.632	-7.73	-6.49	-5.93	-5.59	-5.36	-5.18	-5.03	-4.92
350,000	0.591	-7.59	-6.39	-5.85	-5.52	-5.29	-5.11	-4.97	-4.86
300,000	0.547	-7.43	-6.28	-5.76	-5.44	-5.21	-5.04	-4.91	-4.79
250,000	0.500	-7.26	-6.15	-6.65	-5.34	-5.13	-4.96	-4.85	-4.72
0,000	0.460	-7.10	-6.04	-5.56	-5.26	-5.05	-4.89	-4.76	-4.65
000	0.410	-6.90	-5.90	-5.43	-5.15	-4.95	-4.79	-4.67	-4.57
00	0.365	-6.71	-5.76	-5.31	-5.04	-4.85	-4.70	-4.58	-4.48
0	0.325	-6.53	-5.62	-5.20	-4.94	-4.75	-4.61	-4.49	-4.40
1	0.289	-6.36	-5.49	-5.09	-4.84	-4.66	-4.52	-4.41	-4.32
2	0.258	-6.20	-5.37	-4.99	-4.74	-4.57	-4.44	-4.33	-4.25
3	0.229	-6.04	-5.25	-4.89	-4.65	-4.49	-4.36	-4.26	-4.07
4	0.204	-5.89	-5.15	-4.79	-4.56	-4.41	-4.28	-4.19	-4.10
5	0.182	-5.75	-5.04	-4.70	-4.48	-4.33	-4.21	-4.41	-4.03
6	0.162	-5.62	-4.94	-4.61	-4.40	-4.15	-4.14	-4.05	-3.97

Note: **The capacity susceptances given in this table are for solid wires; a stranded wire has a capacity susceptance about 3 per cent. greater. For special cables having hemp cores use the susceptance corresponding to the actual diameter of the table; the susceptance is a function of the diameter, not of the cross section.**

The charging current per mile of *single phase* line (2 miles of wire) is equal to the above factors multiplied by the volts between wires; for a *three phase line* the charging current per wire per mile of line (3 miles of wire) is equal to the product of the above factors and the volts between wires multiplied by 1.155.

Appendix

The following table, giving the per cent. power loss per mile per 1000 kw. delivered at unity power-factor over a three-phase copper line, will be found useful in determining the size of wire required to transmit a given amount of power under given conditions.

PER CENT. POWER LOSS PER MILE PER THOUSAND KILOWATTS DELIVERED THREE-PHASE SYSTEM, COPPER WIRE, UNITY POWER-FACTOR.

Size B. & S.	Cir. mils	Pounds per mile 3-stranded wires		Kilovolts delivered									
		Copper	Aluminum	2	6	10	20	30	40	50	60	80	100
	500,000	24,200	7,290	2.7	0.31	0.11	0.027	0.012	0.0069	0.0044	0.0031	0.0017	0.0011
	450,000	21,700	6,500	3.1	0.34	0.12	0.031	0.014	0.0076	0.0049	0.0034	0.0019	0.0012
	400,000	19,300	5,830	3.4	0.38	0.14	0.034	0.015	0.0086	0.0055	0.0038	0.0021	0.0014
	350,000	16,900	5,100	3.9	0.44	0.16	0.039	0.017	0.0098	0.0063	0.0044	0.0025	0.0016
	300,000	14,500	4,370	4.6	0.51	0.18	0.046	0.020	0.011	0.0073	0.0051	0.0029	0.0018
	250,000	12,100	3,650	5.5	0.61	0.22	0.055	0.024	0.014	0.0088	0.0061	0.0034	0.0022
0000	211,600	10,200	3,080	6.5	0.72	0.26	0.065	0.029	0.016	0.010	0.0072	0.0041	0.0026
000	167,800	8,130	2,450	8.2	0.91	0.33	0.082	0.036	0.020	0.013	0.0091	0.0051	0.0033
00	133,100	6,430	1,940	10	1.1	0.41	0.10	0.046	0.026	0.016	0.011	0.0064	0.0041
0	105,500	5,100	1,540	13	1.4	0.52	0.13	0.058	0.033	0.021	0.014	0.0081	0.0052
1	83,690	4,040	1,220	16	1.8	0.65	0.16	0.072	0.041	0.026	0.018	0.010	0.0065
2	66,370	3,220	969	21	2.3	0.83	0.21	0.092	0.052	0.033	0.023	0.013	0.0083
3	52,630	2,540	768	26	2.9	1.0	0.26	0.12	0.065	0.042	0.029	0.016	0.010
4	41,740	2,010	609	33	3.7	1.3	0.33	0.15	0.082	0.053	0.037	0.021	0.013
5	33,100	2,002		41	4.6	1.7	0.41	0.18	0.10	0.066	0.046	0.026	0.017
6	26,250	1,587		52	5.8	2.1	0.52	0.23	0.13	0.084	0.058	0.033	0.021

NOTE: The above table is calculated for copper wire and unity power-factor. The size wire to use under other conditions can be readily found by determining from the table the size of copper wire to use in case the power factor were unity and then for the actual conditions select a wire as follows:

For copper wire and

90 *per cent. power-factor*, take a wire of 25 per cent. greater cross section (on B. & S. gauge a wire larger by one number).

80 *per cent power-factor*, take a wire of 60 per cent. greater cross section (on B. & S. gauge a wire larger by two numbers.

For Aluminum Wire and

100 *per cent. power-factor* take a wire of 60 per cent. greater cross section (on B. & S. gauge a wire larger by two numbers).

90 *per cent. power-factor*, take a wire of twice the cross section (on B. & S. gauge a wire larger by three numbers).

80 *per cent. power-factor*, take a wire of two and one-half times the cross section (on B. & S. gauge a wire larger by four numbers).

For any voltage not given in the table,

the size wire to use can be readily determined by remembering that the cross-section for a given per cent. power loss varies inversely as the square of the voltage; *e.g.*, for 11 kilovolts delivered multiply the cross-section corresponding to 10 kilovolts by $\left(\frac{10}{11}\right)^2 = 0.83$.

Example. 20,000 kilowatts is to be transmitted 30 miles over a three-phase system with a total loss in the line of 10% of the power delivered, the delivered pressure to be 60,000 volts; to find the size wire required.

The power loss per mile per 1000 kw. delivered is

$$\frac{10}{30 \times 20} = 0.017 \text{ per cent.}$$

From the table the nearest size copper wire corresponding to 60 kilovolts and a loss of 0.017 per cent. is No. 1 B. & S. (this will give a total loss slightly greater than 10 per cent.) If the power-factor of the load at the end of the line is 90%, No. 0 copper should be used (see note below table); if the power-factor is 80%, No. 00 wire should be used.

If aluminum is to be used, the size wire under the various conditions would be; for unity power-factor, No. 00; for 90% power-factor, No. 000, and for 80% power-factor, No. 0000.

When the size and kind of wire has been determined, the exact power loss and pressure drop can be calculated by the formulas given on the preceding pages.

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INDUCTION MOTORS FOR MULTISPEED SERVICE WITH PARTICULAR REFERENCE TO CASCADE OPERATION

BY H. C. SPECHT

During the last ten or fifteen years a great deal of work has been done toward perfecting methods for varying the speed of induction motors. Each of these methods has certain disadvantages, which have precluded the general adoption of any one of them for practical use. The method most generally applied for varying the speed is that of inserting resistance in the secondary circuit. This method of speed regulation, however, has the one great disadvantage that, for a certain load and speed a certain amount of resistance is required; and as soon as the load changes, the resistance must be changed in order to maintain the same speed. When the load is taken off the motor will return to its synchronous speed. It is also evident that such speed regulation can be obtained only by a great sacrifice of efficiency, due to the high ohmic losses in the secondary circuit.

For work which does not require large size motors, the above method might be satisfactory. For motors of large size, there are as a rule only two or three different speeds required; in such cases good efficiency and power-factor, and a good speed regulation for all loads and speeds are wanted. Motors which fulfil these conditions and which are best known are the following:

1. Independent motors with different numbers of poles, the rotors of which are mounted on the same shaft.

2. A single motor with separate windings, each of which is connected for a certain number of poles.

3. A single motor with one winding, which can be connected for different number of poles.

4. An induction motor, the secondary of which is connected to a synchronous motor.

5. Two induction motors connected either in direct or in differential concatenation or as single motors.

It is the intention in this paper to discuss mainly the characteristics and the operation of motor sets as mentioned in the last paragraph.

The motors of the cascade set are ordinary induction motors with wound secondaries, the rotors of both motors being mounted on the same shaft or interconnected mechanically by other means. The primary of the first motor is connected to the line circuit and its secondary winding to the primary winding of the second motor, which may be the stator or the rotor. The secondary of this last motor is short-circuited direct or through an external resistance.

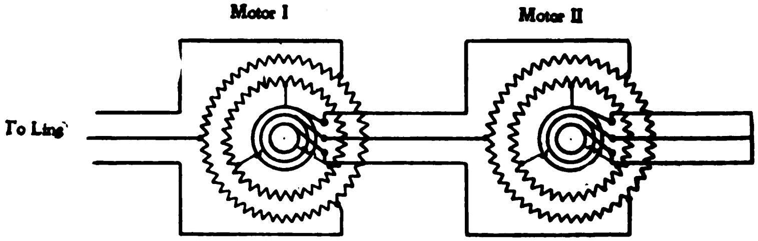

Fig. 1.—Concatenation diagram of motors arranged in direct concatenation

The two motors are connected in direct concatenation if they have a tendency to start up in the same direction, the synchronous speed being then $= \frac{\text{cycles} \times 120}{p_1 + p_2}$, where p_1 is the number of poles of motor I and p_2 the number of poles of motor II. (See Fig. 1).

When the two motors tend to start in directions opposite to each other, they are connected in differential concatenation and have a synchronous speed of $\frac{\text{cycles} \times 120}{p_1 - p_2}$ (Fig. 2).

We shall first investigate the changes of slip, frequencies, voltages, and magnetizing current in each motor when they are connected either in direct or differential concatenation and running at different speeds.

NOTATIONS

n_1 = Synchronous speed of motor I, running as single motor.
n_2 = Synchronous speed of motor II, running on secondary circuit of motor I.
n = Speed of the motor set.
c_1 = Frequency in the line circuit.
c_2 = Frequency in secondary of motor I and primary of motor II.
c_2' = Frequency in secondary of motor II.
e_1 = Voltage on primary of motor I.
e_2 = Voltage induced in secondary of motor I.
e_2' = Voltage induced in secondary of motor II.
p_1 = Number of poles in motor I.

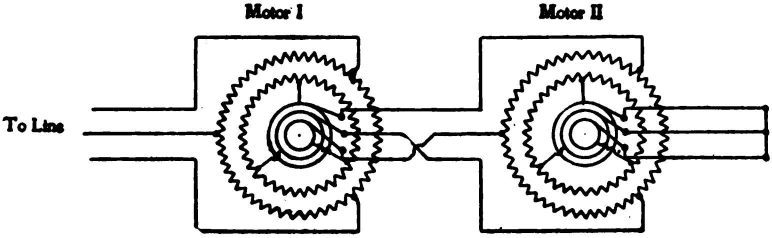

FIG. 2.—Concatenation diagram of motors arranged in differential concatenation

p_2 = Number of poles in motor II.
t_1 = Winding turns in primary of motor I.
t_2 = Winding turns in secondary of motor I.
t_1' = Winding turns in primary of motor II.
t_2' = Winding turns in secondary of motor II.
s_1 = Slip of motor I.
s_2 = Slip of motor II.
s = Slip of motor set.

The slips of motor I and motor II may be expressed by:

$$s_1 = \frac{n_1 - n}{n_1} = 1 - \frac{n}{n_1} \qquad (1)$$

$$s_2 = \frac{n_2 \mp n}{n_2} = 1 \mp \frac{n}{n_2} \qquad (2)$$

The minus sign in the last equation is to be used when motors are connected in direct concatenation and the plus sign when motors are connected in differential concatenation.

The synchronous speeds of motor I and motor II may be determined from

$$n_1 = \frac{c_1 \times 120}{p_1} \tag{3}$$

$$n_2 = \frac{c_2 \times 120}{p_2}$$

In the latter formula the frequency (c_2) in the primary of motor II is equal to $c_1\, s_1$ and n_2 may then be expressed by:

$$n_2 = \frac{c_1 \,.\, s_1 \,.\, 120}{p_2} \tag{4}$$

Formulas (1) and (2) combined, give

$$s_2 = \frac{n_2 \mp n_1\,(1-s_1)}{n_2} = 1 \mp \frac{n_1}{n_2}\,(1-s_1) \tag{5}$$

Formulas (3) and (4) combined, give

$$\frac{n_1}{n_2} = \frac{1}{s_1} \,.\, \frac{p_2}{p_1}$$

and this latter equation placed into formula (5) gives

$$s_2 = 1 \mp \frac{1-s_1}{s_1} \,.\, \frac{p_2}{p_1} \tag{6}$$

or

$$s_1 = \frac{1}{1 \mp (s_2-1)\,\frac{p_1}{p_2}} \tag{7}$$

These last two equations, (6) and (7), show how the slip of one motor depends on the slip of the other motor. If, for instance, the slip of motor I equals 1, the slip of motor II will also equal 1; if $s_1 = 0$ then s_2 will equal infinity.

Since the primary of motor II is connected to the secondary of motor I, the frequency in both these members is the same, and equals:

$$c_2 = s_1 c_1 \tag{8}$$

The frequency in the secondary of motor II is

$$c_2' = s_2 c_2 = s_1 s_2 c_1$$

Replacing s_2 by its value in formula (6), we obtain

$$c_2' = s_1 c_1 \left(1 \mp \frac{1-s_1}{s_1} \cdot \frac{p_2}{p_1}\right)$$

or

$$c_2' = c_1 \left[s_1 \mp (1-s_1) \frac{p_2}{p_1}\right] \tag{9}$$

Assuming that the drop of voltage in the two motors is comparatively small and may, therefore, be neglected, the induced voltages in the windings of the two motors at different speeds may be expressed as follows:

$$e_2 = s_1 \cdot \frac{t_2}{t_1} \cdot e_1 \tag{10}$$

$$e_2' = s_2 \cdot \frac{t_2'}{t_1'} \cdot e_2 = s_1 s_2 \cdot \frac{t_2}{t_1} \cdot \frac{t_2'}{t_1'} \cdot e_1$$

The value of s_2 from formula (6) inserted, gives

$$e_2' = \frac{t_2}{t_1} \cdot \frac{t_2'}{t_1'} \cdot s_1 \cdot \left(1 \mp \frac{1-s_1}{s_1} \cdot \frac{p_2}{p_1}\right) \cdot e_1$$

or

$$e_2' = \frac{t_2}{t_1} \cdot \frac{t_2'}{t_1'} \cdot \left[s_1 \mp (1-s_1) \frac{p_2}{p_1}\right] \cdot e_1 \tag{11}$$

The above equations, (10) and (11), give the values of e_2 and e_2'. To obtain the exact values of the voltages e_2 and e_2', it would be necessary to know the magnitude as well as the direction of the current vectors in the different members and the ohmic as well as the inductive resistance of the windings. This would mean a simple geometrical summation of voltages.

Let us now ascertain how the magnetizing currents change with the speed. When motor I is running as a single motor, the line circuit has to excite this motor only, and as is generally known, the magnetizing current for a given motor will be constant if the induced voltage and frequency remain constant, independent of the speed. Since in direct or differential concatenation the second motor is connected to the first, the line circuit must also furnish the exciting current for this second motor. From formulas, (8) and (10), we know that the induced voltage in the secondary of motor I (which at the same time is the voltage on the primary of motor II) changes in the same ratio as the frequency, the drop in the windings being ignored as before. Under no-load condition, to neglect this drop will not lead to any appreciable error.

Since the voltage e_2, on the primary of motor II changes directly with the frequency c_2, the magnetizing or no-load current in this motor will also remain constant at the different speeds. The exception to this is, that when motor I is running at its synchronous speed, the frequency and voltage of the primary of motor II become zero, with the result that the magnetizing current also becomes zero. And, as the vectors of the magnetizing currents of the two motors are practically in the same phase, they may be added numerically after being reduced to equal voltage. This sum would represent the total magnetizing or no-load current, and would be the same whether motors were connected in direct or differential concatenation.

To prove the correctness of the above formulas, tests as follows could be made:

(A) MOTORS CONNECTED IN DIRECT CONCATENATION

Secondary of the second motor open-circuited, and the set driven mechanically by a third motor of variable speed characteristics. At different speeds the frequencies, voltages, and amperes to be taken in all members, the voltage and frequency on the primary of motor I to be held constant.

Example of actual test and calculation. Both motors wound 3-phase, of which motor I was designed for 8 poles, 50 cycles, 400 volts and motor II for 4 poles, $16\frac{2}{3}$ cycles, 77 volts. The ratio of turns in motor I was

$$\frac{t_2}{t_1} = 0.58$$

and that of motor II was

$$\frac{t_2'}{t_1'} = 0.66.$$

Fig. 3 represents the different values when motors are connected in direct concatenation. These values are derived from the previous formulas and have been proved by actual test.

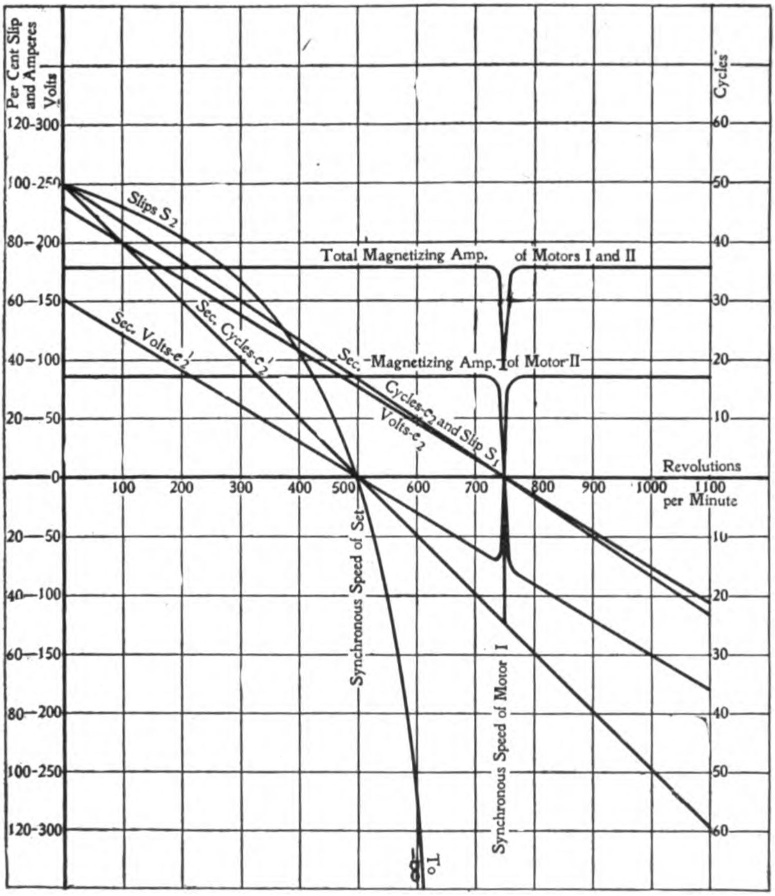

FIG. 3.—Motors connected in direct concatenation. Secondary of motor II open-circuited

The conditions at zero speed are practically identical with those of a stationary transformer connected in cascade. With increase of speed the induced secondary voltages (e_2; e_2') and the frequencies ($c_2; c_2'$), of motors I and II, the slip (s_1) of motor I and slip (s_2) of motor II decrease. At the synchronous speed of the cascade set (500 rev.per min.) e_2', c_2', and s_2 drop to zero and above that speed they become negative, which indicates that motor II acts as an induction generator.

At 750 rev.per min., motor I reaches its synchronous speed and it follows that e_2, c_2, and s_1 become zero. Consequently the secondary frequency, the voltage, and the magnetizing current of motor II should drop suddenly to zero, which, in fact, they do as is found by actual test. (In Fig. 3 the magnetizing current of motor II is reduced to primary voltage of motor I).

Formulas (9) and (11), however, do not show this, because the drop is not taken into consideration and because our previous assumption is correct only for relatively small drops. In the vicinity of the synchronous speed of motor I, (750 rev.per min.) the induced voltage in its secondary is very small and as the magnetizing current of motor II remains constant, if the voltage increases in the same ratio as the frequency, the drop in voltage amounts here to quite a percentage. Even if there were no losses in the motors, it might be of interest to note that our mathematical formulas do not agree fully with the physical laws.

As the magnetizing current of motor II at 750 rev.per min. drops abruptly to zero, the primary current of motor I is equal to the magnetizing current of motor I. This was also proved by test.

By increasing the speed of the cascade set still further, *i.e.*, above 750 rev.per min., motor I becomes a generator and motor II again a motor.

(B) MOTORS CONNECTED IN DIFFERENTIAL CONCATENATION

Tests to be made in the same manner as in (A). The results of test and calculations are shown in Fig. 4. We learn from the curves in Fig. 4, that at zero speed the voltages (e_2; e_2') and the frequencies ($c_2; c_2'$) are of full value and that the slips ($s_1; s_2$) of both motors are equal to 1 or 100 per cent. All these values, except the slip s_2 and the magnetizing currents, decrease in a certain relation to the speed; at 750 rev.per min., e_2, c_1, s_1 have become zero. The secondary voltage (e_2') and the frequency (c_2') at this speed drop abruptly from half their full values to zero, owing to the zero voltage and frequency in the primary of motor II.

The slip (s_2) of motor II increases from 1, slowly at first, but gradually faster and faster until infinity. Taking into consideration the several rotations of the fields as well as data given above, we find that up to this speed, 750 rev.per min., both machines act as motors. At 750 rev.per min., motor I runs at its synchronous speed; and since the cycles in the primary of motor II have dropped to zero and further, since motor II formerly ran in the direction opposite to its normal rotation, the speed of motor II corresponds to the infinite value.

Owing to the fact that in motor II the frequency and volts are zero, it is obvious that at the synchronous speed of motor I there is no tendency in the motor set itself to rise to the synchronous speed of the differential concatenated connection. Other means must be resorted to in order to obtain this speed. After the set has been speeded up it will stay there and will carry load. One way to speed up the set is to start it by using another motor; another way is to connect the motor having the smaller number of poles with the line and when the set reaches synchronous speed switch over to the normal operating connection.

It is not advisable to leave the motor having the smaller number of poles on the line because the frequency in the circuit connecting the motors will be of double magnitude. The total iron losses of the set would, therefore, be considerably greater, causing a drop in the efficiency and also causing a higher temperature rise.

Considering now the curves of the pass from 750 to 1500 rev.per min. (see Fig. 4), we observe that the secondary voltage (e_2) and the frequency (c_2) of motor I become negative and at 1500 rev. per min. reach their full negative value compared with the positive values at standstill.

The voltage (e_2') and frequency (c_2') in the secondary of motor II drop gradually to zero. The slip (s_2) of motor II has changed at 750 rev.per min. from +infinity to –infinity and has at 1500 rev.per min. the final value of zero.

In reviewing this data, bearing in mind the field rotations in both motors, we observe that at a speed above 750 rev.per min., motor II becomes an induction generator which forces a frequency into the secondary of motor I. This frequency has a field rotation opposite to that of the primary of motor I. The result is that the rotor of motor I must run at a speed corresponding to the sum of the primary and secondary frequencies (c_1 and c_2) in order to be in synchronism.

Since the primary voltage (e_2) of motor II varies directly with its frequency (c_2,) the magnetizing current of motor II remains constant, ignoring the drop in the windings.

At 750 rev.per min., however, the magnetizing current of this motor will suddenly drop to zero owing to absence of voltage and frequency. As the magnetizing current of motor I is constant and has practically the same power factor as the magnetizing current of motor II, these currents can be added numerically (when reduced to the same voltage as is done in Fig. 4), to get the total magnetizing current of the set. This current will be the same as in direct concatenation.

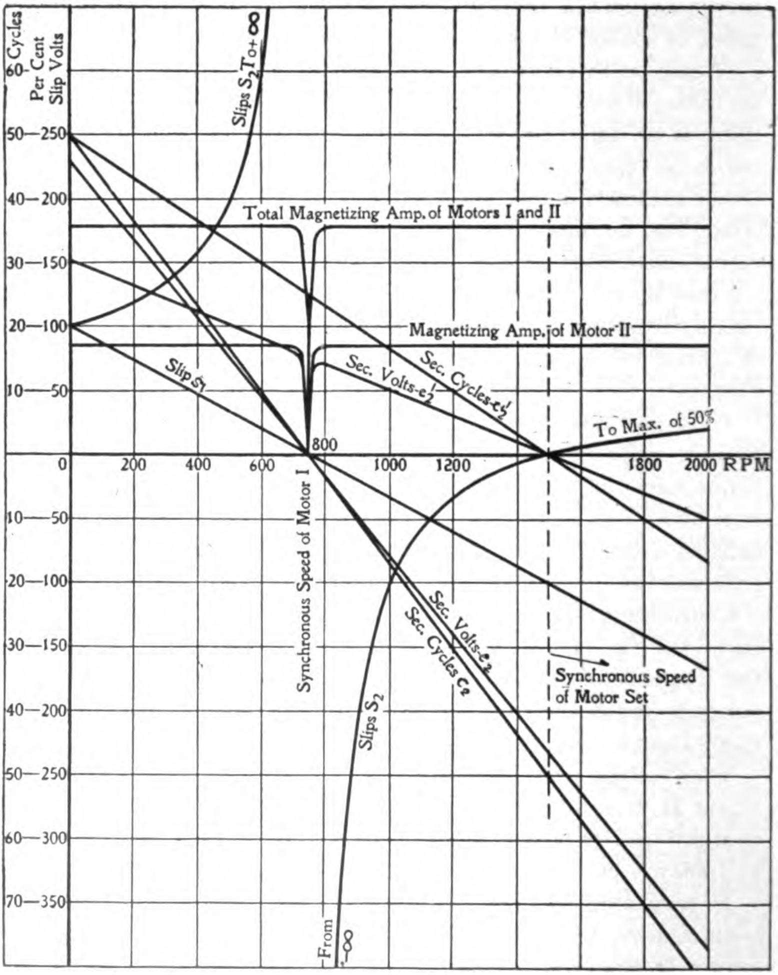

FIG. 4.—Motors connected in differential concatenation. Secondary of motor II open-circuited

Conditions with secondary of motor II closed. In the foregoing it has been shown that with motors connected either in direct or differential concatenation, running at their synchronous speed, the frequency and voltage in the secondary winding of motor II is zero. Therefore, the short-circuiting of this winding would not affect conditions in the other members. When the motor set is running on load the speed will be somewhat lower. In each winding there will be a certain frequency and voltage and, therefore, some current. The voltages, magnetizing amperes, and frequencies of all members may be taken from Figs. 3 and 4 respectively, and by taking into consideration the drop in the winding, it is possible to determine the actual currents which flow. The primary current (i_1) in motor I is made up of its magnetizing current (i_{01}) and its secondary current (i_{2},) which form a triangle. The secondary current of this motor is at the same time the primary current of motor II and this current again is made up of the magnetizing current (i_{02}) and secondary current (i_2') of motor II, which also form a triangle. (See Fig. 5.)

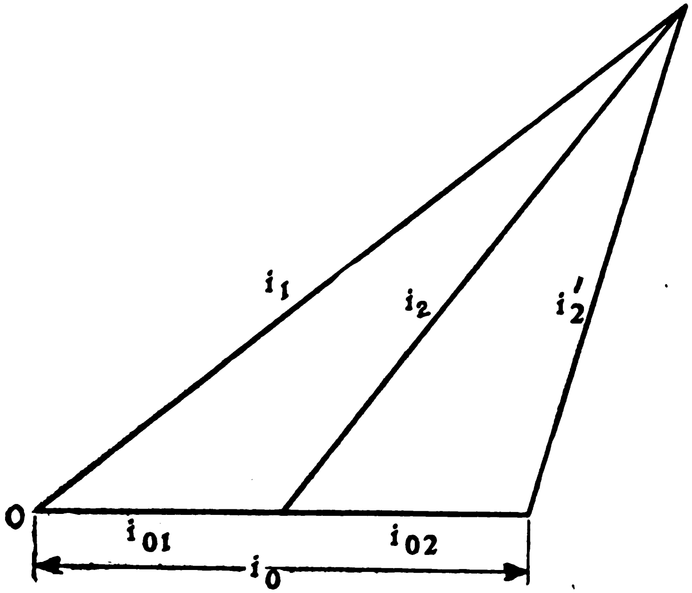

Fig. 5.—Vector diagram of currents in motor set

The two vectors of the magnetizing current (i_{01}) and (i_{02}) are practically in line as mentioned before.

The inductive resistances and the corresponding induced voltages vary directly with the frequency, the ohmic resistances being generally small in comparison with the inductive resistances. Therefore, considering the voltages as constant, the inductive resistances, according to this theory, must also be considered constant. An induction motor is equivalent to a circuit with ohmic and inductive resistances, providing the winding turns are reduced to the same voltage. To a certain extent, this is also true of a motor set connected either in direct or differential concatenation as shown in Fig. 6.

In the above:

r_1 = Ohmic resistance in primary of motor I.
x_1 = Inductive resistance in primary of motor I
r_2 = Ohmic resistance in secondary of motor I.
x_2 = Inductive resistance in secondary of motor I.
R_1 = Ohmic resistance in secondary representing resistance corresponding to load of motor I.

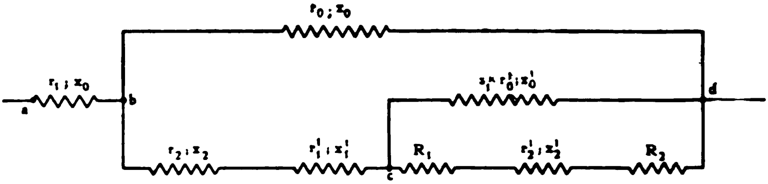

FIG. 6.—Schematic diagram of motor set

r_1' = Ohmic resistance in primary of motor II.
x_1' = Inductive resistance in primary of motor II.
r_2' = Ohmic resistance in secondary of motor II.
x_2' = Inductive resistance in secondary of motor II.
R_2 = Ohmic resistance in secondary representing resistance corresponding to load of motor II.
r_0 = Ohmic resistance representing the factor of iron loss in motor I.
$s_1 r_0'$ = Ohmic resistance representing the factor of iron loss in motor II.
x_0 = Inductive resistance representing the factor of the magnetizing current in motor I.
x_0' = Inductive resistance representing the factor of the magnetizing current in motor II.

In Fig. 6 everything remains constant except $s_1' \, r_0'$, R_1 and R_2. The resistance representing iron loss in motor II varies directly with the slip of motor I approximately. R_1 and R_2 vary inversely with the slip (s) of the set approximately.

It is apparent in Fig. 6, that with increase of load or increase of amperes, the voltage across the points ($c\ d$) decreases on account of the drop in voltage in the section ($a\ c$). This results in a decrease of magnetizing current in motor II. The question now is, what will this change amount to. According to formula (10), the voltage (e_2) of the secondary of motor I, (which is also the primary voltage of motor II), depends mainly on the slip (s_1) of motor I and this slip depends in turn on the ratio of the number of poles in both motors and on slip (s_2) of motor II. If for instance, the number of poles in motor II is small in comparison with the number of poles in motor I, the slip (s_1) will be small, as will be also the voltage (e_2). Therefore, the drop in the windings will be proportionately large ; *i.e.*, the change in the magnetizing current (i_{02}) will be great with the variations of load. In most cases, however, the ratio of the number of poles in motor II to those of motor I is not greater than 1 to 3, and if motors are properly designed the magnetizing current in motor II will remain practically constant within those limits which are of interest in determining performances. Assuming that our conclusions are as nearly correct as commercial use requires, and providing that the slip of the motor set is not too large, we can consider the two motors as a single one; *i.e.*, at different loads the factors in Fig. 6 will remain constant with the exception of R_1 and R_2.

It would now be an easy matter to demonstrate that the extremities of the current vectors for the different loads travel on a circle.[1]

To draw up the diagram circle the following test data are required:

1. Primary and secondary amperes and primary watts of motor I, running in direct concatenation (or differential concatenation as the case may be) at full voltage.
2. Primary amperes and watts with motor set locked, to be taken at any voltage, preferably at approximately half voltage, these tested values to be reduced to full voltage.
3. Secondary voltages of motor I and II, when standing still and secondary of motor II open-circuited.
4. Ohmic resistance of primary and secondary windings of

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[1] *Electrical World & Engineer*, Feb. 23, 1905, "Practical Diagram for Induction Motors."

motor I and of primary winding of motor II. All resistances to be reduced to the primary of motor I.

To show how the diagram circle is obtained from few test values and how the performances are derived from the same, the following example is made use of:

Motor I, 60 h.p., 400 volts, 50 cycles, 8 poles, primary as well as secondary wound, three-phase in star.

Motor II, 60 h.p., 77 volts, $16\frac{2}{3}$ cycles, 4 poles, primary as well as secondary wound, three-phase in star.

These two motors were connected in direct concatenation, the primary of motor II being connected to the secondary of motor I, and the primary of motor I to a line circuit of three-phase, 400 volts, 50 cycles, and finally the secondary of motor II short-circuited.

(1) No-Load Readings

i_0 = 71.4 amperes, total in primary of motor I.
i_{02} = 34 amperes, total in secondary of motor I, reduced to primary winding.
P_0 = 3.1 kw. no-load losses.

(2) Locked Readings

i_L = 412 amperes in primary of motor I.
P_L = 64.6 kw. in primary of motor I.

(3) Motors at Rest, Secondary of Motor II Open-circuited

Voltage $e_2 = 232$ and $e_2' = 153$.

(4) Resistance per leg Reduced to Primary Winding of Motor I and to a Temperature Corresponding to Continuous Full-Load Run

r_1 = 0.11 ohms in primary of motor I.
r_2 = 0.104 ohms in secondary of motor I.
r_1' = 0.064 ohms in primary of motor II.
r_2' = 0.046 ohms in secondary of motor II.

In Fig. 7, the vertical axis represents the direction of the voltage impressed into primary of motor I; the quadrant *A B* with its center *O* and with a radius of 100 parts represents the power-factor circle.

To determine the center of the diagram circle, first lay off to a convenient scale the no-load and locked current vectors

$$O\,C_0 = 71.4 \text{ amperes,}$$

and

$$O\,C_L = 412 \text{ amperes,}$$

in the direction of their respective power-factors.

$$\cos\phi_0 = \frac{P_0 - [i_0^2\, r_1 + i_{02}^2\,(r_2 + r_1')]}{i_0\,.\,e_1} = 0.0825$$

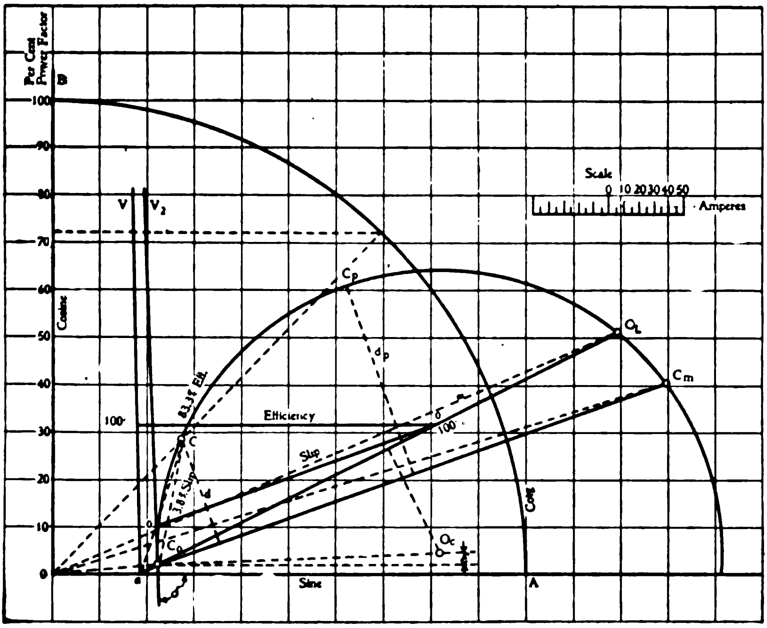

FIG. 7.—Circle diagram

$$\cos\phi_L = \frac{P_L}{i_L\,.\,e_1} = 0.392$$

Then from C_0 draw the line $C_0\,O_c$ making an angle ε with the base line

$$\tan\varepsilon = \frac{i_0\,r_1 + i_{02}\,(r_2 + r_1')}{e_1} = 0.0339$$

The intersection of the line perpendicular to the middle of $\overline{C_0 C_L}$ with the line $\overline{C_0 O_c}$ is the center of the diagram circle. The line $\overline{C_0 C_L}$ represents the base line for the output; *i.e.*, the distance from any point on the circle above $\overline{C_0 C_L}$ to this line ($\overline{C_0 C_L}$) multiplied by a certain constant gives the horse power output for the corresponding current vector.

The line which connects the points C_0 and C_m represents the base line for torque; the point C_0 is already known and point C_m can be determined by

$$\operatorname{cotan} \phi_m = \frac{r_1 + r_2 + r_1'}{X_1 + X_2 + X_1' + X_2'}$$

Herein is:

$$X_1 + X_2 + X_1' + X_2' = \frac{\sin \phi_L \;.\; e_1}{i_L} = \frac{0.92 \times 400}{412} = 0.893 \text{ ohms}$$

$$\text{and } r_1 + r_2 + r_1' = 0.278 \text{ ohms}$$

Therefore:

$$\operatorname{cotan} \phi_m = \frac{0.278}{0.893} = 0.311$$

The torque for any current vector is equal to the distance from the corresponding point on the circle to the line ($C_0 C_m$) multiplied by a certain constant which may be easily calculated from:

$$\frac{5250 \times \text{horse power output}}{\text{speed}} = \text{lb. torque at 1 foot radius.}$$

Tangent ($C_0 V_2$) to the current circle at C_0 is the base line for the secondary copper losses. Therefore a line with a convenient scale of 100 parts drawn between $\overline{C_0 V_2}$ and $\overline{C_0 C_L}$ and parallel with ($C_0 C_m$) gives the slip scale. A line from C_0 through any current point on the circle indicates the percentage of slip on the latter scale, reading from left to right.

A line ($a V$) drawn through the intersection (a) of line $\overline{C_0 C_L}$ with $\overline{O A}$ and which makes approximately an angle with $\overline{O A}$ equal to $\frac{1}{2}$ $(90^\circ + < \delta)$, (δ being the angle of $\overline{V C_0}$ with $\overline{O A}$) represents the base line for the total losses. Therefore, a convenient scale between this line and $\overline{C_0 C_L}$ and parrallel to $\overline{O A}$ represents the efficiency scale, *i.e.*, a line from (a) through any current point of the circle will indicate on the scale the percentage of efficiency. As an example Fig. 7 shows the results for point C only, which are as follows:

$\overline{O\,C}$ = 124 amp. (total); efficiency = 83.3 per cent.; slip = 3.8 per cent.; power factor = 72 per cent. From these we calculate

$$\text{Horse power output} = \frac{\text{amperes} \times \text{volts} \times \text{efficiency} \times \text{power-factor}}{746}$$

$$\text{Horse power output} = \frac{124 \times 400 \times 0.833 \times 0.72}{746} = 40$$

$$\text{Horse power input} = \frac{\text{amperes} \times \text{volts} \times \text{power-factor}}{746} = 48.2$$

$$\text{Speed of motor set} = 500\,(1-0.038) = 481 \text{ rev. per min.}$$

$$\text{Lb. torque at 1 ft. radius} = \frac{5250 \times \text{horse power output}}{\text{speed}}$$

$$\text{Lb. torque at 1 ft. radius} = \frac{5250 \times 40}{481} = 437$$

Data for all other loads may be obtained in the same way as in above. The maximum torque; *i.e.*, the pull-out torque of the motor set, is equal to the maximum distance d_p multiplied by a constant, which might be determined from the above load of point C constant $= \frac{\text{lb. torque}}{d} = \frac{437}{d}$. Consequently maximum torque $= \frac{d_p}{d} \times 437$ = 788 lb. at 1 ft. radius.

All the data derived from this diagram checked up to within a fraction of 1 per cent. with the results obtained by test and by calculation.

In the same way as described above we may obtain the data for motors connected in differential concatenation.

Comparing now these results with those which might have been obtained from two independent motors, one having 12 poles and the other 8 poles, and together having the same amount of material as the complete cascade set, we find the following: The efficiency and power-factor will be somewhat higher if each motor has the same maximum torque as the cascade set. Nevertheless, the cascade set has certain advantages over a set composed of two independent motors. A few of the more important points of advantage are: greater latitude in design, a more flexible and a simpler speed control, and safer operation.

For instance, in a cascade set the individual motors may be designed so as to have greater width and smaller diameter, thus keeping the peripheral speed lower than would be the case with a single motor for the speed of direct concatenation. In cascade connection each motor tends to balance the other, consequently the speed regulation is more smooth; that is, the change from slow to high speed or from high to slow speed can be made gradually without any mechanical jarring or electrical choking effects. For example, a change from slow to high speed can be accomplished by inserting a high resistance across the circuits connecting motors I and II and then cutting out resistance gradually with the increase in speed until the set reaches the normal speed of motor I, or any other between that of synchronism of motor I and that of cascade connection as may be desired; all other connections to remain unchanged. In a case where three or four different speeds are wanted, it is obvious that a cascade set can be built very much more cheaply than three or four independent motors. For instance with two motors, motor I having 10 poles and motor II 6 poles and at a line frequency of 60 cycles, the following synchronous speeds can be obtained:

1. Motor 1 and II in direct concatenation 450 rev. per min.
2. Motor I runs single 720 rev. per min.
3. Motor II runs single 1200 rev. per min.
4. Motor I and II in differential concatenation 1800 rev. per min.

It should be noted that the above speeds are possible with a set consisting of a 10-pole motor and a 6-pole motor. Other combinations of speeds may, of course, be obtained by changing the number of poles. However, in any combination of motors the speeds have a certain arbitrary relation to each other. For this reason the four speeds obtained might in some cases not be the ones desired; that is, some of them could be the ones wanted while the others would not be.

In comparing the different methods of varying speeds of induction motors we find that each method has some advantage over the others when considered in connection with certain classes of work. But at the same time, there are certain disadvantages to be found in all these methods. The operation of a cascade set is simple and safe even if the efficiency and power factor are not altogether the best, on account of the increased inductance.

The elimination of this objection depends, it would seem, on the development of an efficient and practical phase compensator.

A paper to be presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., June 29-July 2, 1908.

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A NEW LARGE GENERATOR FOR NIAGARA FALLS

BY B. A. BEHREND

A new generating plant of considerable magnitude has been completed recently at Niagara Falls. This plant is the new plant of the Niagara Falls Hydraulic Power and Manufacturing Company. A number of large direct-current generators to be used for the manufacture of aluminum has been installed in this plant, each generating unit consisting of two direct-current generators connected to 11,000-h.p. turbines. A large alternating-current generator, one of an aggregate of three wound for 12,000 volts, has also been installed in this station. The power house is located at the foot of the falls, on the American side, below the old power house of the Niagara Falls Hydraulic Power and Manufacturing Company.

The generator which is described in this paper offers a number of interesting features and is remarkable among the generators at Niagara Falls on account of its speed of 300 rev. per min., which is greater than the speed of any of the other large generators installed in the power houses at the falls. The generator is wound for 12,000 volts, three-phase, 25-cycles. The waterwheel is mounted on a horizontal shaft and has a capacity of 11,000 h.p. The generator is rated at 6500 kw. with a capacity for continuous operation of 7320 kw., or approximately 7500 kw. The runaway speed of the waterwheel is given as 506 revolutions; the generator, therefore, had to be designed to be safe at this speed.

The experience which has been gained from the design of generators for direct connection to steam turbines has greatly minimized the difficulties of a problem like the one under consideration. Nevertheless, 11,000-h.p. generating units are neither so plentiful nor so readily designed and built as not to afford considerable interest, especially if the results obtained with such machines are remarkably satisfactory.

The object of this paper is to illustrate, by a number of photographs and drawings, the design and construction of this interesting unit, and to show by the tests the electrical characteristics.

Fig. 1 shows the generator assembled on the test floor.

Fig. 2 shows the stator of the generator with the rotor removed.

Fig. 3 shows the rotor by itself.

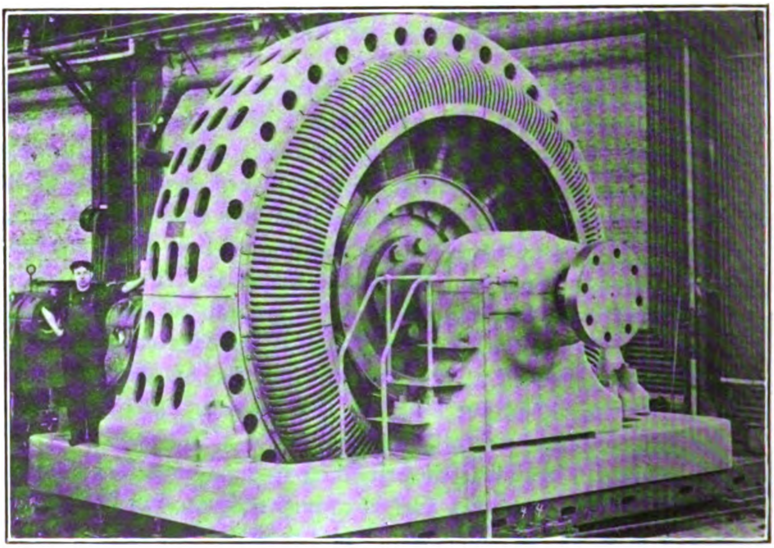


Fig. 1—10,000 h.p. generator

Fig. 4 shows one of the pedestals and the two stands for supporting the brush studs for the field excitation. The field excitation is derived from 220 volts.

Fig. 5 is an assembly drawing showing the most important details.

The construction of the rotor is worthy of careful study. A disc of nickel-steel, without a hole in the centre, forms the middle part of the revolving element. Two nickel-steel rings are mounted on each side of this web and are bolted and keyed to it. The nickel-steel used for this construction must have great mechanical strength and high magnetic permeability. A nickel-steel containing 3.5 per cent. nickel has been used for this purpose. Its elastic properties are.

Elastic limit	50,000 lb. per sq. in.
Ultimate strength	80,000 lb. per sq. in.
Elongation	20 per cent. in 2. in.
Reduction of area	40 per cent.

The magnetic qualities of this steel are given in the curve

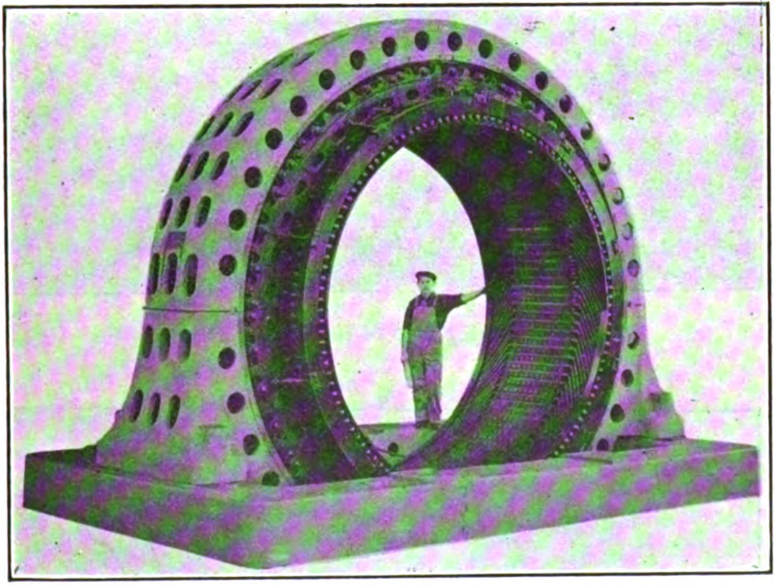


FIG. 2—Stator of 10,000 h.p. generator

illustrated by Fig. 6. The nickel-steel forgings as used in this construction enable the designer to produce the strongest and lightest construction, as the mechanical strength of the material is great and the magnetic permeability high. The weight of the complete rotor is only 92,900 lb. and, the bearings being 16 in. by 50 in., the specific pressure is only 58 lb. per sq. in. The weight of the stator is 116,700 lb. and the weight of the entire machine is 275,000 lb.

It may be of interest to discourse briefly upon the theory of elastic stresses in rotating discs and rings. The theory of

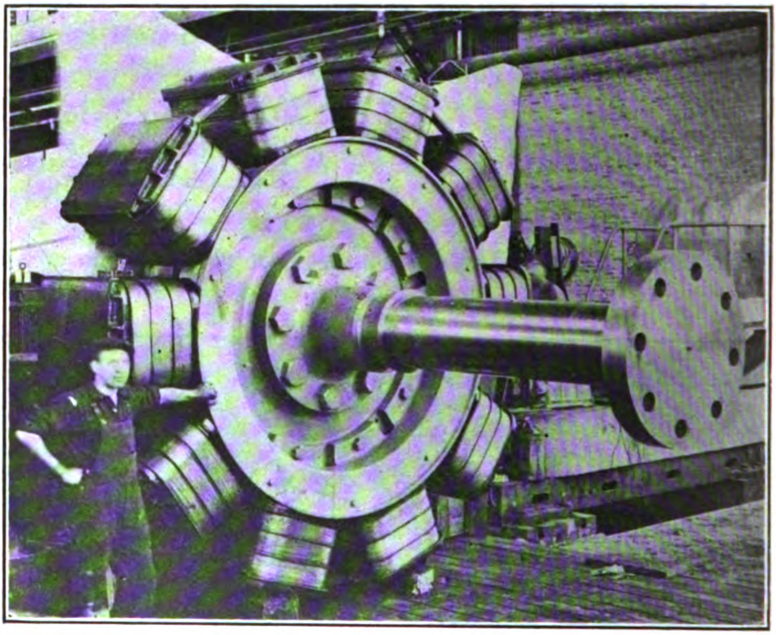


FIG. 3.—Revolving field of 10,000 h.p. generator

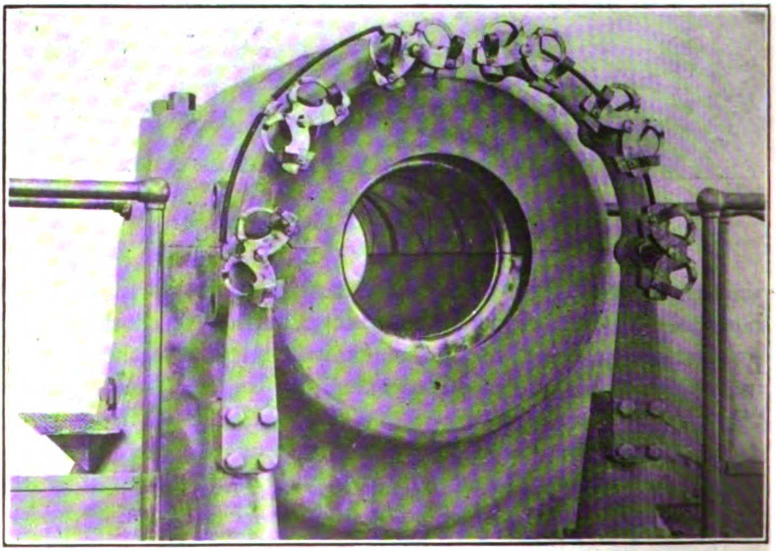


FIG. 4—Pedestal and brush stands of 10,000 h.p. generator

elasticity applied to the radial and tangential stresses in rotating discs shows that the point of maximum stress is at the centre of a disc and at the inside surface of a ring. We have demonstrated the correctness of this theory by experiments with lead discs, the deformation of which, as obtained by measurement before and after the test, readily indicates that the maximum deformation, as shown by the lateral contraction, appears at the centre of the discs or at the inside of the ring from where the metal flows toward the outside portions. The radial stress normal to a free surface must be zero, and, therefore, the maximum

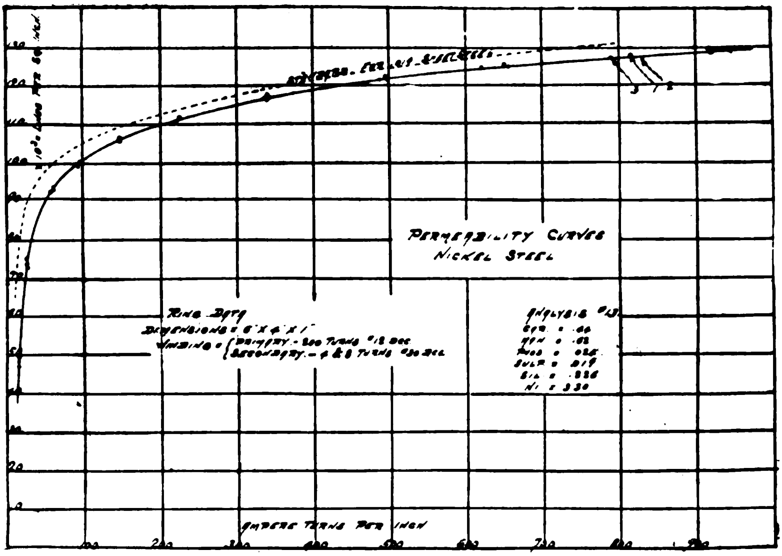
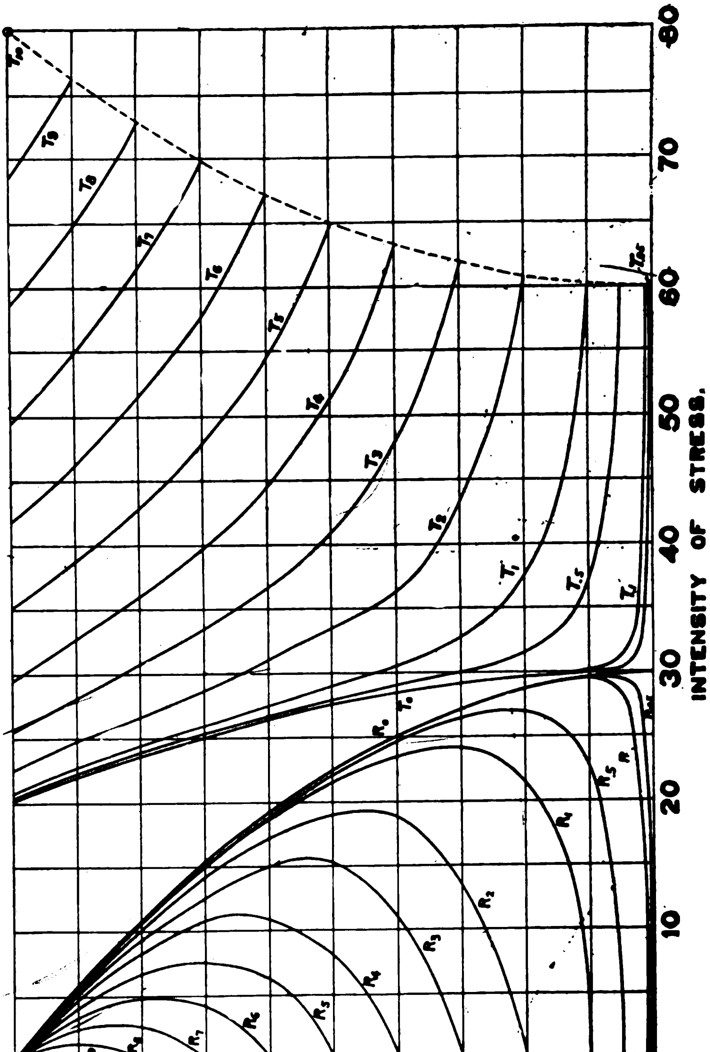


FIG. 6

stress appears as a tangential stress. In a solid disc the elements at the centre are subject to both radial and tangential stresses. A hole in the centre eliminates the radial stress, and, as is shown by the theory, this doubles the tangential stress. This is well illustrated in the curves shown in Fig. 7, in which the radial stresses are shown by the abscissas on the left of the curve sheet, and the tangential stresses are shown by the abscissas on the right of the curve sheet. It is assumed that the outside radius of the disc, or the ring, is kept constant and equal to 10 units of length, while the inside radius is increased from zero to 10 units of length. The radial and tangential stresses are then represented by the abscissas of the two sets of curves shown in the figure. Great mechanical strength and lightness are obtained in this rotor construction, and although it would have



CURVES OF STRESSES, IN A ROTATING DISC OR ANNULUS.

OUTER RADIUS=10. R=RADIAL STRESS. T=TANGENTIAL STRESS. SUBSCRIPT INDICATES INNER RADIUS.

FIG. 7

been possible to use a hub mounted on a shaft, according to the practice with slow-speed machinery, as the stresses on the inside of the hub would not have been prohibitive, the design adopted

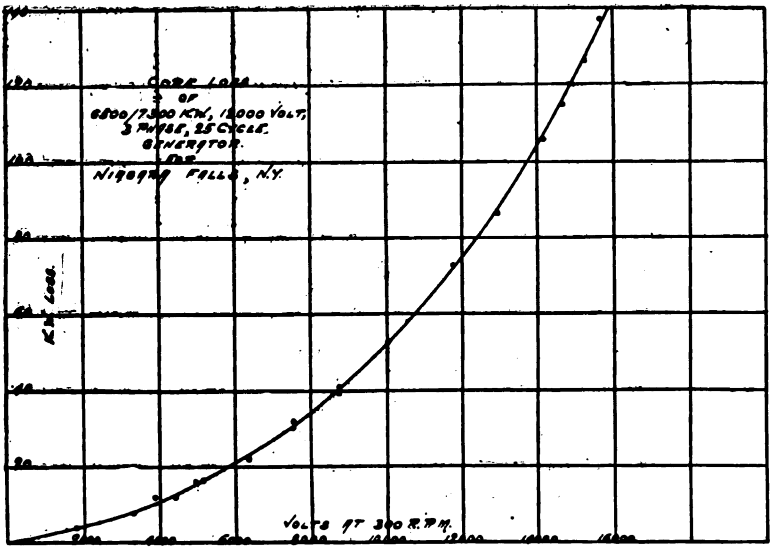


FIG. 8—Core loss of 10,000 h.p. generator

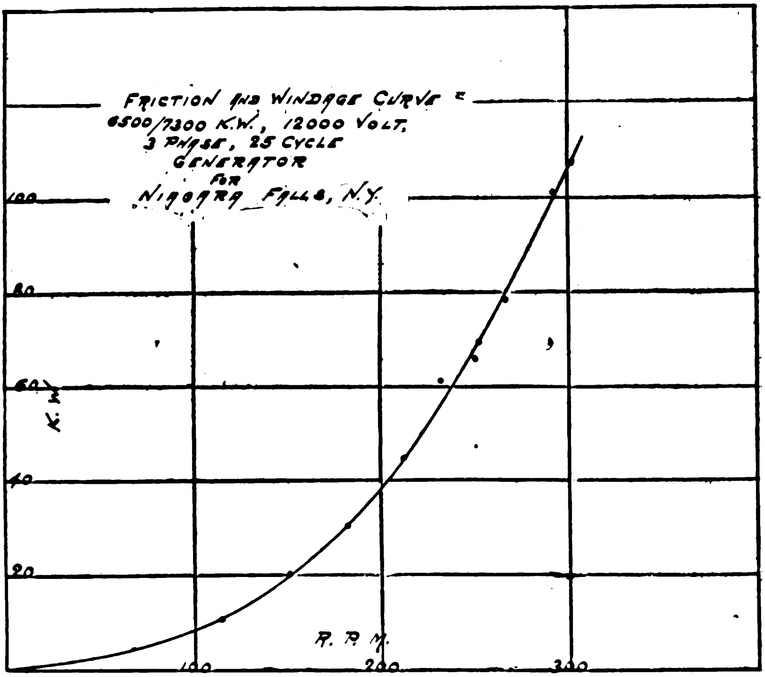


FIG. 9—Friction and windage curves of 10,000 h.p. generator

for this large generator is elegant and mechanically superior. The electrical characteristics of this unit are well shown in the curves, Fig. 8 to 12, accompanying this paper.

Fig. 8 represents the core-loss which is equal to 75 kw. at 12,000 volts; this is approximately one per cent. of the output.

Fig. 9 represents the power necessary to overcome the friction and windage at 300 rev. per min. which is equal to 106 kw.

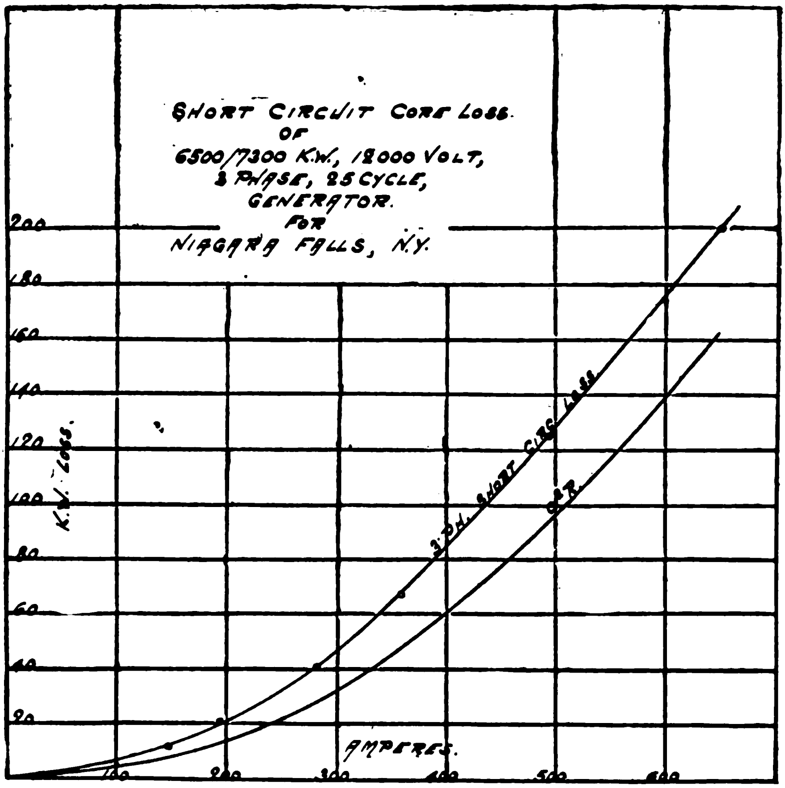


Fig. 10—Short-circuit core loss of 10,000 h.p. generator

Fig. 10 represents the short-circuit core-loss of the generator, demonstrating that the ratio of the short-circuit loss to the $I^2 R$ loss, at 7500 kw., is equal to 1.45, which is a very excellent result.

Fig. 11 represents the saturation and regulation curves of the generator with a regulation of 8.4 per cent. at full load and 100 per cent. power-factor at 12,000 volts. The generator is

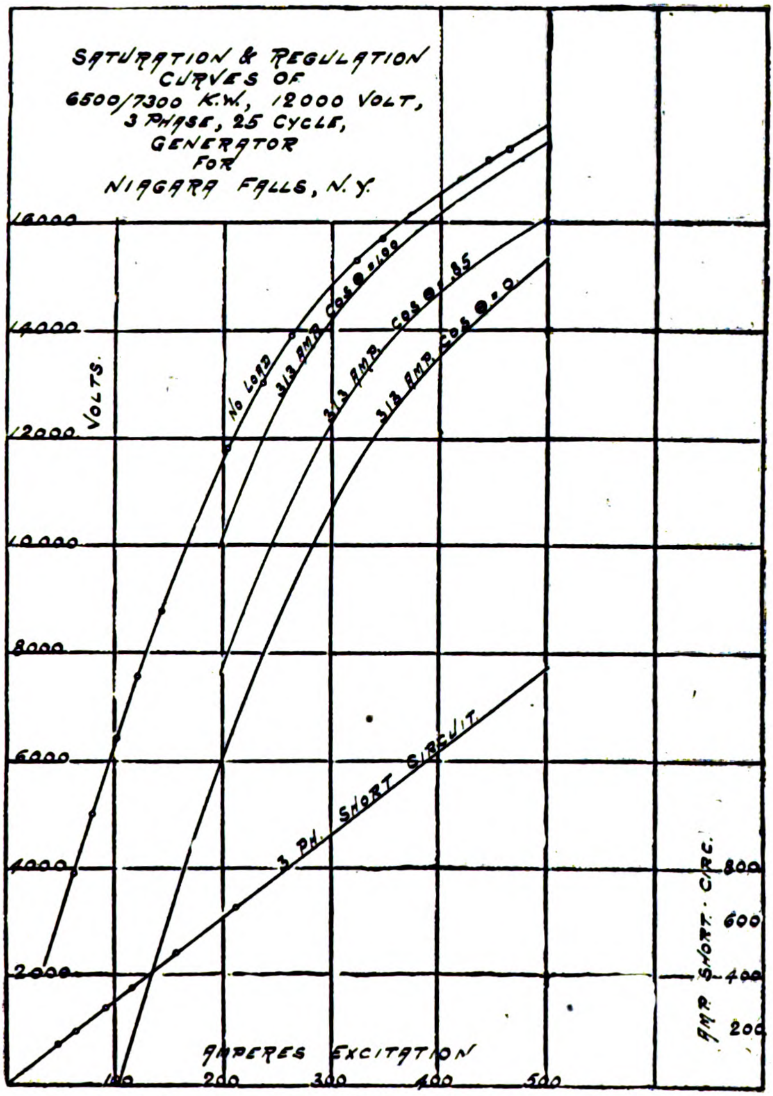
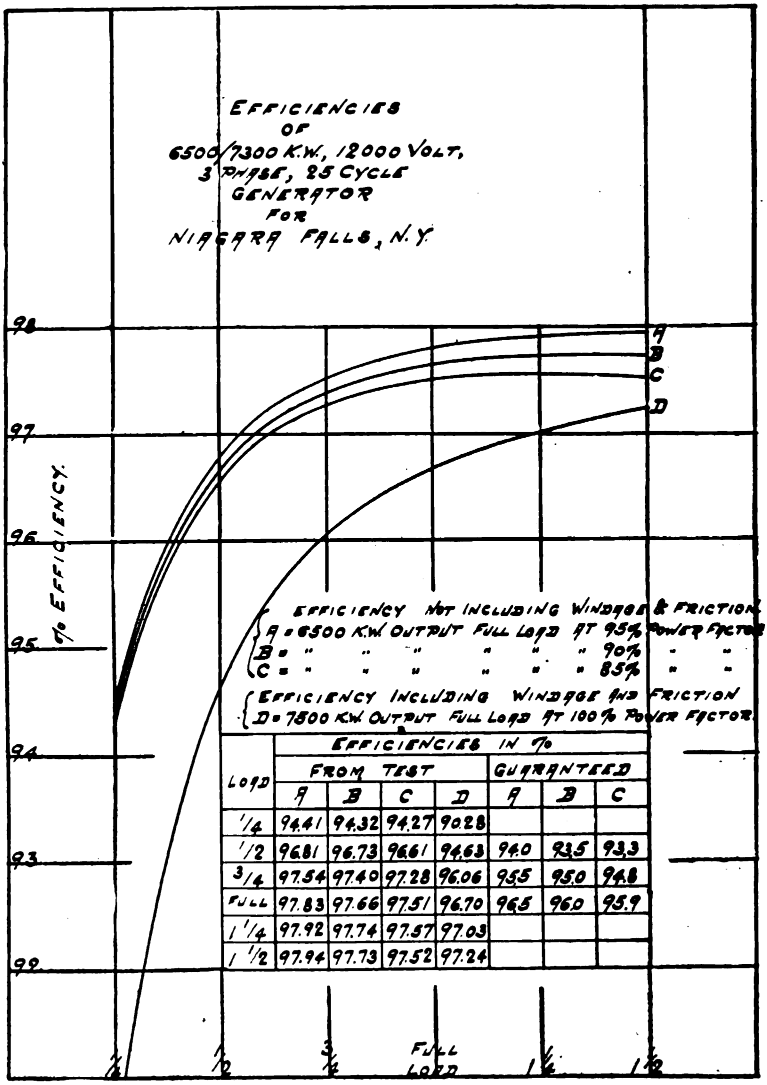


FIG. 11—Saturation and regulation curves of 10,000 h.p. generator



EFFICIENCIES
OF
6500/7300 K.W., 12000 VOLT,
3 PHASE, 25 CYCLE
GENERATOR
FOR
NIAGARA FALLS, N.Y.

EFFICIENCY NOT INCLUDING WINDAGE & FRICTION
A = 6500 K.W. OUTPUT FULL LOAD AT 95% POWER FACTOR
B = " " " " " " 90% " "
C = " " " " " " 85% " "

EFFICIENCY INCLUDING WINDAGE AND FRICTION
D = 7500 K.W. OUTPUT FULL LOAD AT 100% POWER FACTOR.

LOAD	EFFICIENCIES IN %						
	FROM TEST				GUARANTEED		
	A	B	C	D	A	B	C
1/4	94.41	94.32	94.27	90.28			
1/2	96.81	96.73	96.61	94.63	94.0	93.5	93.3
3/4	97.54	97.40	97.28	96.06	95.5	95.0	94.8
FULL	97.83	97.66	97.51	96.70	96.5	96.0	95.9
1 1/4	97.92	97.74	97.57	97.03			
1 1/2	97.94	97.73	97.52	97.24			

FIG. 12—Efficiency curves of 10,000 h.p. generator

capable of giving 13,000 volts under any condition of load that is likely to occur, should this be required.

Fig. 12 shows several efficiency curves and a tabulation of the guaranteed efficiencies compared with the actual efficiencies.

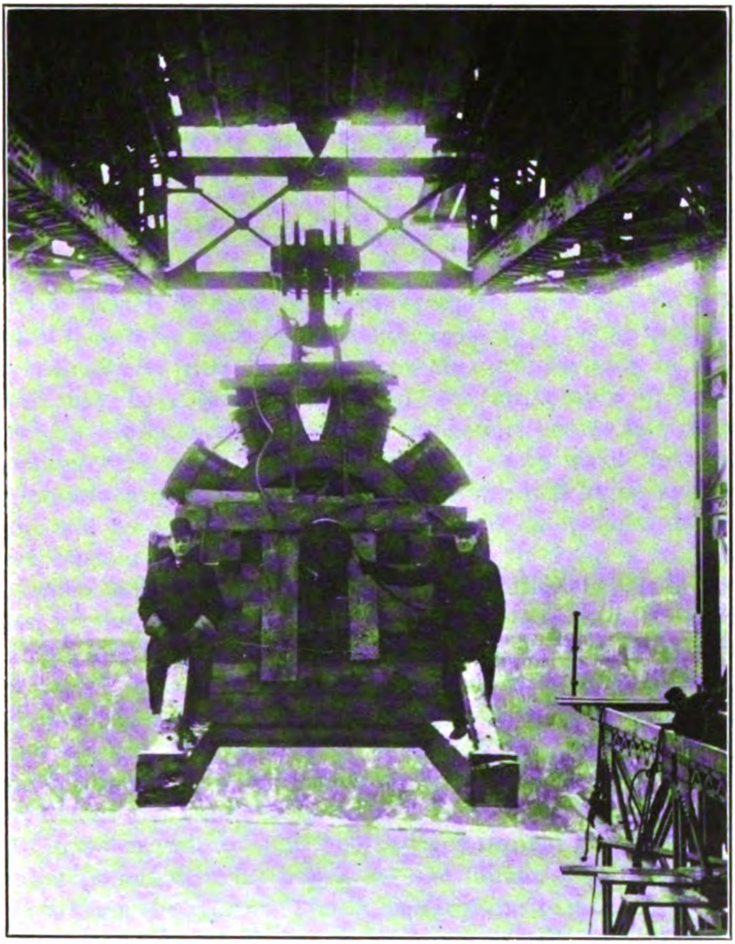


Fig. 13—Revolving field on its way down the cliff

Fig. 13 shows the revolving field suspended from a crane from the cliff, 240 ft. above the Niagara River, as it was being lowered into the gorge.

From the tests made regarding the heating of this unit, the temperature will remain within 35 degrees at normal load and 40 degrees at 7500 kw. The power of this generator is going to be used chiefly for the operation of induction motors in Niagara Falls and its vicinity.

A paper to be presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., June 29–July 2, 1908.

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THE RELATION OF THE MANUFACTURING COMPANY TO THE TECHNICAL GRADUATE

BY B. A. BEHREND

Even though in times of business depression it may seem to us as if there were more applicants than positions, yet no thoughtful man denies that, while the number of positions in such times may have greatly decreased, the importance of filling them by thoroughly capable and competent people has correspondingly increased. For example, a position which, in times of exceptional prosperity may be filled fairly well by an average man, will be sorely in need of a man of exceptional ability when business prosperity is on the wane. If there is any one fact more patent than another it is the fact that there is always room at the top of the ladder for men of integrity, of moral courage, and of intellect. There are plenty of men who possess any one of these qualities; there are few who possess all three, and these the manufacturing companies, or the world at large, most require. In their anxiety to secure the raw recruits for officers thus endowed, the manufacturers turn of necessity to the universities and their graduates.

It must be granted that the colleges possess an almost unlimited potentiality for improving the human material turned over to them to shape and polish, and, it seems to me, considering the results obtained, they are doing very well in this shaping and polishing process. But they are not always supported in the right direction by the manufacturing companies. To allude to one instance only, I refer to the manner in which the manufacturing company seeks the young graduate, instead of letting him do the seeking. He thus gains, at the outset, an exaggerated idea of his importance, and an independence which is not conducive to the development of those qualities which make thoughtful and painstaking men. Our graduates are chiefly deficient in these qualities, and this is due, not so much to an innate deficiency in this direction, as to the fact that the incipient faculty has never been properly awakened and cultivated. There is abroad amongst our colleges and their graduates a most ominous disdain for painstaking accuracy and devotion to laborious detail, so essential to all really great work in engineering. The wish to take someone-else's thought and work and make it a commercial success, which is so prominent a feature of our business life, is easily explainable, though not so easily excusable. Men of ability realize that the same effort turned into the channels of commercial work will be productive of better returns than they would obtain by painstaking working out, for instance, the design and construction of electrical machines. In this case, even though their work may have met with eminent commercial success, our business methods are not much concerned with a debt of gratitude or obligation to the men that did the building up. Here lies a menace to the stability and continued prosperity of our manufacturing industries which must, in time, be remedied, lest it produce a far-reaching result in discouraging graduates of our colleges from the pursuit of new and important creative engineering work, with the result that we will have to draw on other countries for a supply of well-trained engineering brains.

The managers of our manufacturing plants can do as much toward the development of right views and proper education, as can the teachers and organizers of the colleges. The former need to study more sympathetically the condition of the latter, and *vice versa*. There are very poor pretenses of both managers and teachers in this world, and it is obvious that " the highest gifts are not always brought to the highest place." Education is a very good thing, but it cannot give the qualities which it should develop. Those who, like the writer, have been instrumental in the building up of large manufacturing organizations, recognize that the absence of moral qualities frequently mars a successful career, as frequently, perhaps, as the absence of purely intellectual qualities. Success often accompanies the work of men possessing ability, untempered by scrupulous restraint. Examples of this kind, so plentiful, have left a detrimental impression on the minds of aspiring young men. The thoughtful words of Mr. James Bryce, that this country " . . .

has the glorious privilege of youth, the privilege of committing errors without suffering from their consequences ", remind us that many of our faults are not visited upon us with the unerring justice they deserve, because of the actual and potential wealth of this country in its present state of youthful and vigorous development. But let us not be deceived permanently into believing that, with our population increasing in geometric progression and thickening in our cities and manufacturing centers, many of the crude and lavish methods, despite which our industry is the most flourishing in the world, can be permanently retained without doing infinite harm. Space does not permit me to do more than to indicate the line of thought I wish to suggest. We need both character and intellect in our graduates, which should be cultivated by close cooperation between the manufacturing companies and the colleges, but for creating which no panacea has as yet been devised.

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MEASUREMENTS OF LIGHTNING, ALUMINUM LIGHTNING-ARRESTERS, EARTH RESISTANCES, CEMENT RESISTANCES, AND KINDRED TESTS

BY E. E. F. CREIGHTON*

During the past year investigations have been continued in the study of lightning and the operation of lightning-arresters on transmission lines. Another effort was made to supplement laboratory studies with experimental measurements on transmission lines. Two lines were chosen well up in the Rocky Mountains of Colorado as offering the greatest facilities both from the interest of the managers and the frequency and severity of lightning storms. New types of apparatus were developed for measurements and new data were collected. The object of this paper is to describe briefly the instruments and methods used in the measurement of duration, potential, current, frequency, and the theory and practise of lightning protection and earth connections with data collected during two years of study; also resistance measurements of cement under the heating effect of dynamic current, and comments on the action of lightning-arresters.

The scope of the work is represented by the following index of subject-matter:

CHARACTERISTICS OF LIGHTNING

Lightning duration.

Duration apparatus.

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* The writer wishes to acknowledge his indebtedness to Mr. J. A. Clay, superintendent and operating engineer of the Animas Power & Water Co., for many courtesies in the installation of the apparatus, and for subsequent auxiliary reports; to Mr. W. N. Clark for courtesies extended while observations were being taken on the high-tension lines of the Pueblo & Suburban Light & Power Co.

Lightning potential.
Apparatus for measuring lightning potential.
Lightning current.

SUBDIVISION OF FREQUENCY

Frequency of recurrence.
Frequency multiple stroke.
Natural frequency of discharge.
Very high frequency.
Quantity of lightning {*fuse apparatus*
ballistic apparatus.}
Movement of charge on parallel wires.

MISCELLANEOUS OBSERVATIONS

Pueblo and Suburban Light and Power Company.
Animas system.
Lightning recorder.
Records of discharges.
Lightning alarm.
Equipment for study.
Note on choke-coils.
Experience with a grounded phase.
Direct stroke of lightning.
Wooden versus metallic cross-arms.

GENERAL COMMENTS ON THE ARRESTER EQUIPMENT OF THE ANIMAS COMPANY

Location of arresters.
Characteristics of the gap aluminum arrester.
Lightning alarm and the fuse.
Aluminum arresters for direct currents.
Temporary and permanent critical voltage of film.

EARTH CONNECTIONS

Methods of tests of earth resistance.
Pipe earth resistance per foot of depth, Fig. 21.
Effect on the resistance of varying the distance between pipes.
Treatment to improve earths.
Multiple pipe earth connections.
Animas earth test.
Variation of resistance with depth.
Time resistance variation after salting.
Measurement of resistance between pipes and groups.

Measurements between sub-stations.
Measurements of resistance of tree, pole, and railroad earths.
Earths carrying dynamic current.
Form of pipe earth recommended.
Station grounds, resistance factor.
Station grounds, inductance factor.
Station grounds, permanence factor.
Lightning conductors for protecting buildings.

CEMENT AS A RESISTOR

Effect on resistance of cement of various proportions of sand.
Change in resistance with age.
Behavior of cement resistors on constant potential circuits.
Effect of moisture on resistance.
Conductivity at high temperatures or pyro-conductivity.
Change from moisture conductivity to pyro-conductivity.
Concrete as a resistor.
Summary and conclusions on concrete resistance.

CHARACTERISTICS OF LIGHTNING

Before a lightning-arrester can be designed along logical lines the characteristics of the discharge which may pass through it must be known. A complete analysis of lightning phenomena on electrical transmission lines has been given by Dr. Steinmetz.* This analysis is necessary to a thorough understanding of the theory of the subject.

In considering the design of lightning-arresters, a brief classification based on the effects of lightning may be made as given below. The principle factors involved are:

1. Duration of the surge of lightning.
2. The potential values of the lightning.
3. The maximum current discharge rate.
4. The natural frequency of the lightning.
5. The quantity of electricity in the lightning stroke.

In considering the choice and operation of arresters for a transmission line, the most important of these factors is the duration of the surge. These factors will now be discussed in more detail.

1. *Duration of lightning.* Lightning from an external source (cloud lightning) is usually of very short duration. Measurements made during the summer of 1907 in Colorado, gave a

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* PROCEEDINGS A.I.E.E., March 1907.

range of 0.04 sec. to 0.0001 sec. Cloud lightning has been known to continue for longer than one-half a second in rare cases. Lightning from an internal source (accidentally grounded phase, switching, etc.) often continues over a period of several minutes, or even several hours.

Lightning frequently recurs in successive strokes. A number of measurements were made on an idle line which gave as high as seven separate discharges in one second. In the lightning-arrester these multiple strokes give the effect of long duration.

FIG. 1

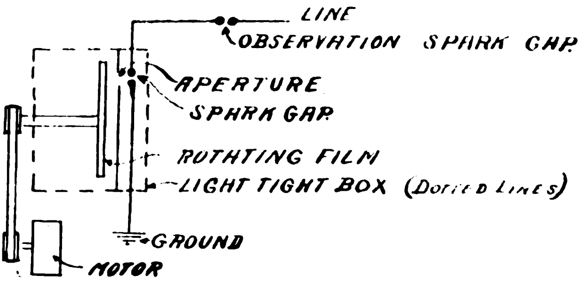

FIG. 1.—Revolving film duration apparatus

The duration apparatus. Two different pieces of apparatus were used to measure the duration of lightning. They are shown diagrammatically in Figs. 1 and 2. For very short duration the apparatus shown in Fig. 1 was used. This apparatus consisted of a spark-gap in front of a rapidly revolving photographic film. Figs. 3, 4, and 5 are records from this machine; they show several different discharges which are made to fall on an unexposed portion of the film by moving in the aperture

FIG. 2.

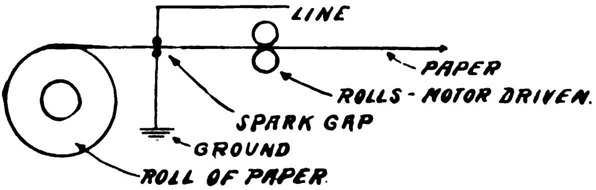

FIG. 2.—Moving tape duration apparatus

to a lesser radius on the film. Knowing the speed of rotation of the film, the duration of the discharge was measured. Calculations were made on 36 discharges. Nearly all of the storms that caused the discharges were distant from the station. This may partly account for so many short durations. There were two strokes expressed in hundredths of a second, seventeen in thousands of a second, and sixteen in ten-thousandths of a second. Besides the duration and multiple strokes, these exposures show frequencies of the order of the line frequency. Each exposure is divided into a broken line which represents the frequency of alternation of the discharge. This frequency, about 3000 cycles per second, was further analyzed into a higher

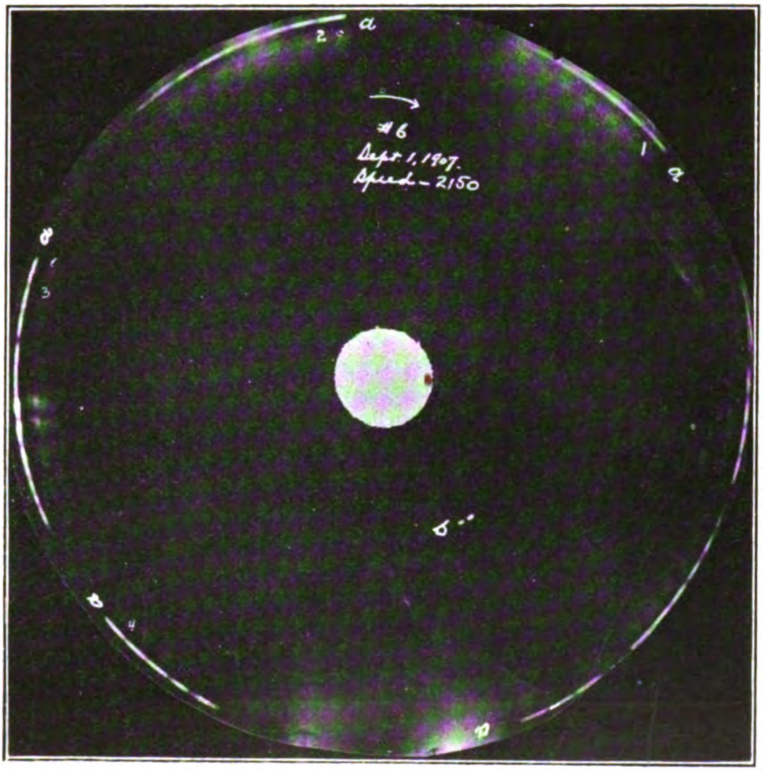

FIG. 3.—Record from revolving film duration apparatus. This shows one multiple discharge consisting of eight single discharges marked (a) and one single discharge marked (b)

frequency by the lightning frequency meter to be described later. Three thousand cycles is beyond the frequency that can be measured by an oscillograph. Where several segments of a circle of the same radius are shown (Fig. 4), multiple lightning strokes occurred; these strokes occurred in such rapid succession that they appeared as one to the eyes focused on the observation spark-gap.

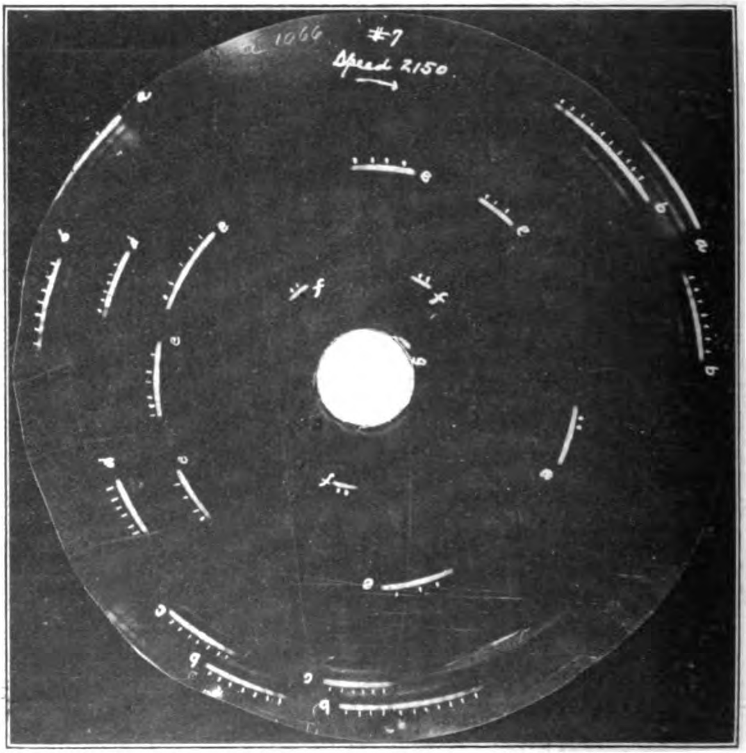

Fig. 4.—Record from revolving film duration apparatus showing six multiple strokes marked *a*, *b*, *c*, *d*, *e*, and *f*. The small dots at the side of most of the exposures are ink marks to emphasize the markings of the natural frequency of the discharge for fear they might not show up in the usual process of reproduction. This record is unusual in the number of multiple strokes

Fig. 5 is the only record of a discharge that did not show a natural frequency of oscillation. This may have been due to earth resistance being exceedingly high under the line where the lightning charge was set free. A fuller explanation is attempted later.

For the measurement of longer durations of lightning, the paper tape apparatus shown in Fig. 2 was used. The tape was drawn through a spark-gap between line and ground at a uniform rate. • This apparatus attached to an idle line showed multiple strokes; in several instances, as many as four strokes were distributed over one second. In these multiple strokes the successive discharges could be detected by the ear. It usually produced a rattling sound. Without the apparatus the noise might have been attributed to echoes. Records of multiple strokes and duration as given by the tape will be shown later in this paper.

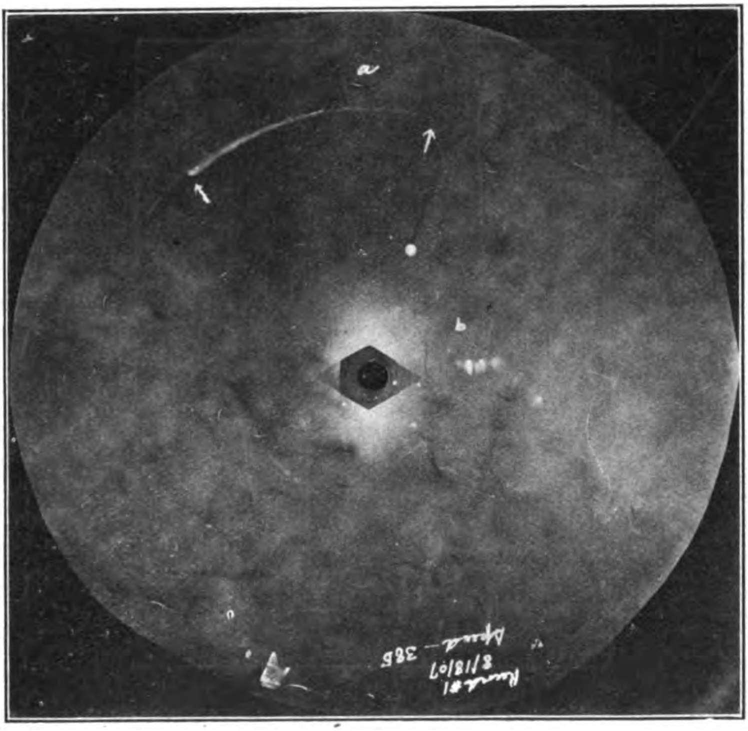

FIG. 5.—Record from the revolving film duration apparatus showing two single discharges. Discharge (a) is the longest one recorded. If there are any natural oscillations the speed of the film is too low to show them

2. *Lightning potential.* In cases of direct strokes from the clouds to a transmission line, the potential at the nearest insulator builds up so rapidly that even the small inductance of the straight line wire presents a relatively high impedance to the flow of the electrical charge along the wires, away from the point, and consequently it spills over the insulators and down the poles to the ground. In this extreme case a lightning-arrester situated some distance away will give no protection to the point struck. If the electrical charge can be prevented from jumping around the insulator by high dielectric strength or overhead ground-wire the charge travels to the nearest lightning-arrester. During this movement it loses greatly in potential and somewhat in natural frequency. In every case of induced static charge from the clouds, lightning potential on the line is always greatest directly under the cloud that is discharging. A number of cases

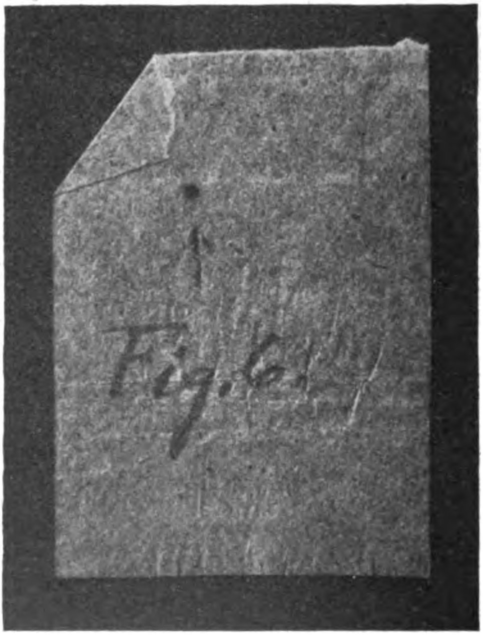

Fig. 6.—An accidental discharge which passed through the right forearm from the wrist to the elbow and out through an arc to an iron support. This produced complete paralysis of the forearm which lasted several hours. The injury was painless except for the after-effects of the surface burns

were observed last summer in Colorado when a storm was over an unprotected station about three miles from the main substation in which the lightning jumped three and one-half inches over switch bushings at the unprotected station instead of being discharged by a gap set at 0.4 in. (one-eighth as large) at the main sub-station.

If the lightning potential is due to an internal surge of electrical energy between static and electromagnetic energy, then the high potential will exist across the junction point of the parts of the circuit acting as condenser and reactance-coil respectively. This may for example, be, one coil or all the coils of a generator or transformer.

Apparatus for measuring potentials. Practically the only apparatus which indicates the potential of lightning of brief duration is the well known needle-gap. A needle-gap without series resistance would short-circuit the dynamic potential and therefore could not be used. The use of a reasonable resistance in series with a single needle-gap affects its spark potential but slightly even for high frequencies. The electricity travels along the resistance and throws the static stress on the needle-gap and produces a spark. The volume of spark which takes place decreases as the resistance increases. Since it is necessary to record this spark the resistance must be kept at least low enough to permit this. As an example of the effect of resistance on the relative spark potential at high frequency the following is given: two needle-gaps placed in parallel, the first set at 1 in. having no resistance, and the second having two 8 in. rods with carborundum as a base, known as 50,000-ohm rods (actually less at high potentials). The second gap would not spark when set on 1 in. but would, without fail, spark simultaneously when set at 0.9 in. The potential, obtained from a leyden jar and static machine, had an initial value of about 60,000 volts, was very suddenly applied, and had a frequency of about two million cycles per second. At 60 cycles the spark potential of the needle-gap was not affected by this series resistance. This condition of high frequency is probably more severe than will be met on a transmission line.

One needle-gap never actually measures lightning potential unless the applied potential should happen to be equal to the spark potential. If a needle-gap sparks it shows the pressure reached its spark potential but it may have gone very much higher. By using several gaps in parallel the potential may be measured with a rough accuracy depending upon the number of gaps in parallel and the differences in their setting. Fig. 7 shows diagrammatically part of such a lightning potential meter.

In each circuit is a fuse, a needle-gap, and a resistance limiting the dynamic current to about one-half ampere. In operation the impressed potential must be between the largest gap that sparked and the next one above. Since the gap must be set after each lightning stroke, the form of the meter is modified to give a measurement of several successive strokes, to record the time, and to give automatic resetting. Fig. 8 shows one leg of this automatic resetting device.

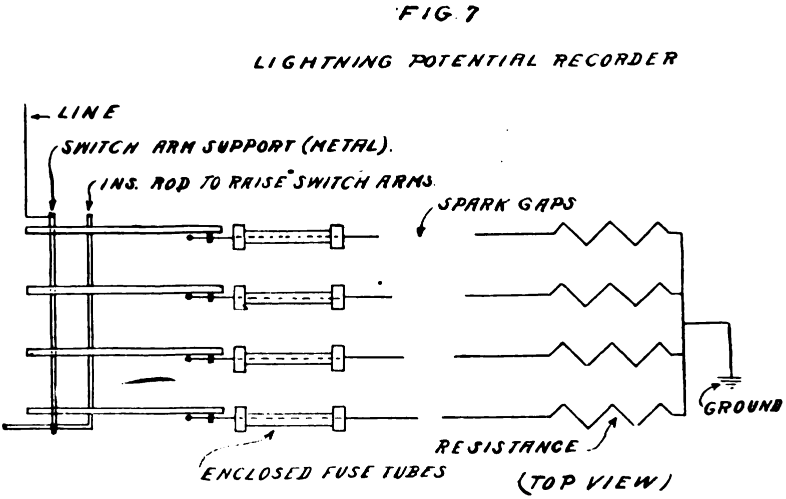
FIG 7
LIGHTNING POTENTIAL RECORDER
LINE
SWITCH ARM SUPPORT (METAL).
INS. ROD TO RAISE SWITCH ARMS
SPARK GAPS
GROUND
RESISTANCE
ENCLOSED FUSE TUBES
(TOP VIEW)

Fig. 7.—Plan of lightning potential recorder

In this leg the gaps are all equal. From the switch arm a thread is run to a pen which draws a line on a paper tape moved by clockwork. This records the exact time when each gap sparks. Since a lightning recording device can be placed on each arrester, the combined results of the two will show the relative efficiency of the arresters for each discharge. For example, the needle-gap of the potential recorder may be set on 2, 2.5, 3, and 4 times normal line potential. To get the proper operation of the potential recorder care must be taken in its design to avoid producing the effect of a grounded phase by the arcing of one phase only.

3. *Lightning current.* The maximum value that the lightning

current may take has an important bearing on the design of the arresters. Until recently it was found necessary and expedient to install some resistance in the arrester circuit to limit the dynamic current which usually follows the lightning discharge. This resistance limits also the lightning discharge current, and by its ohmic drop ($I R$) prevents the lightning potential from decreasing rapidly.

If the lightning discharge current is limited by ohmic resistance it is easy to calculate what current can discharge at double line voltage. Double voltage is usually within the limiting safe value. Such a comparison of arresters gives their relative values of protection against lightning.*

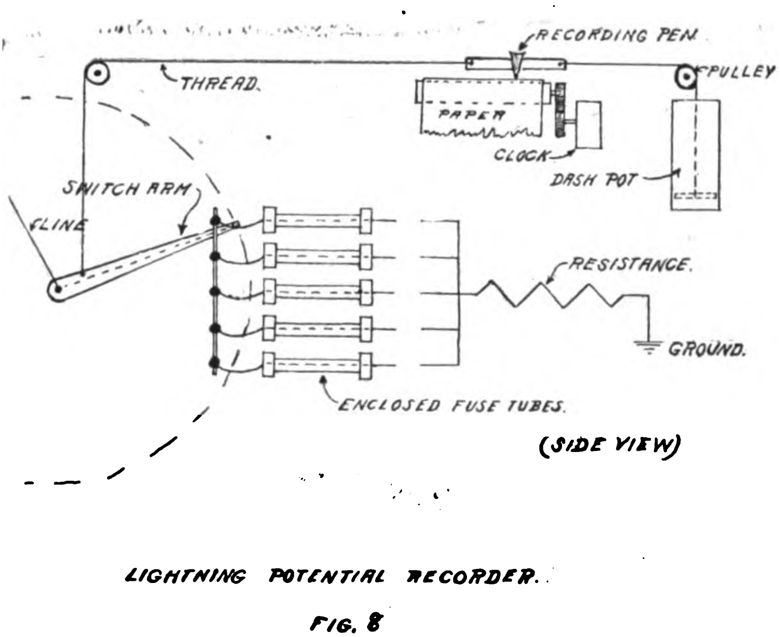

FIG. 8.—Elevation of lightning potential recorder

The actual measurement of the lightning current is usually more difficult than the measurement of the high frequencies. Several conditions will be outlined here. Since concentrated capacity and inductance are used in the laboratory, these equations are convenient to use here.

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* The time constant or natural frequency enters as a factor. A large time constant of the lightning allows of higher resistance in the arrester circuit.

1. In any circuit containing a low resistance, what is the current per volt of impressed electromotive force?

$$I = \frac{2\sqrt{C}}{\sqrt{\ L - R^2 C)}} \qquad \frac{1}{\varepsilon^{\frac{R\,T}{2\,L}}}$$

In which C is the capacity in farads,

L is the inductance in henrys,

R is the total ohmic resistance,

t is the time of one-quarter cycle of the natural frequency.

$$t = \frac{\pi\, L \sqrt{C}}{\sqrt{4\, L - R^2\, C}} \cdot$$

2. What is the maximum current per volt that can flow in any discharging circuit? The limiting value is more valuable for safe design. If R is assumed zero in the above equation, a short and convenient expression for maximum current is:

$$I \text{ max.} = \sqrt{\frac{C}{L}}\ V$$

3. If the frequency is known by measurement or calculation, the current may be derived from the equation

$$I = \frac{V}{L\,\omega}$$

4. The maximum current may be estimated from calculation utilizing the frequency, quantity of electricity, and logarithmic decrement. As an example of calculation of a testing circuit in the laboratory the following is given:

Three one-gallon leyden jars are connected in parallel, and this set is connected in cascade or series with an equal unit by means of about seven feet of No. 0 wire.

Capacity of each jar is about $144 \text{x} 10^{-11}$ farads

Capacity of all the jars is about $216 \text{x} 10^{-11}$ farads.

Inductance is about $24 \text{x} 10^{-7}$ henrys.

I maximum = 0.03 ampere per volt. At 100 kilovolts, the possible maximum current is 3000 amperes.

The frequency is $n = \frac{I}{T} = \frac{1}{2\pi\sqrt{L C}} = 2.25$ millions.

In regard to accuracy of the calculated value of frequency, an error in either capacity or inductance is reduced by the square root in the result. An error of 25 per cent. in these values gives an error of only 5 per cent. in the frequency.

The resistance which will just destroy the oscillatory discharge of the leyden jar circuit in the foregoing description is 7000 ohms.

SUBDIVISION OF FREQUENCY

Natural frequency of lightning should not be confused with the multiple stroke or the frequency of recurrence of strokes. Frequency is distinguished by analysis under four heads.

1. Lightning strokes often come into a station during a storm at an average rate ranging from two per minute to one in five minutes.

2. Each of these flashes, which appears to the eye as a single flash, may often be two or more distinct successive strokes distributed over a second or less. In the next paragraph the analysis of each of these individual strokes into oscillations gives the natural frequency of the discharge.

3. Many of the discharge records of the rotating-film apparatus for measuring duration are in the form of a uniformly broken line whose parts correspond to the half cycles of the discharge current. This frequency, when it existed, was of the order of the natural frequency of the transmission line, about 3000 cycles per second.

4. Each one of these waves may be made up of higher frequencies superimposed upon it. Of these high frequencies the only ones measured were of the order of a millon cycles per second.

Comments and data on the four subdivisions. 1. Frequency of recurrence, or rapidity of lightning discharges. A note of all the discharges during two storms which came into the substation from three circuits and were recorded on the tape lightning recorder is herewith given.

Condensed record of second storm of August 12, 1907. First discharge 1:10:36; last discharge 1:59:4, p.m. Total number of discharges 42. Average number of discharges about one per minute. Maximum number of discharges per minute was three. In the second storm of August 9, 1907, there were 33 strokes in 43 minutes. The rapidity of discharge in these storms was not unusual.

2. *Multiple strokes.* In the second storm of August 12, there were two cases of multiple strokes. In each case there were two strokes within a second recorded on the paper tape. In the second storm of August 9, 1907, there were five cases of multiple strokes. When multiple strokes followed each other more rapidly than 0.2 second, the paper tape would not show a separation. The more rapid multiple strokes are recorded on the duration apparatus, Figs. 3 and 4. Discharge marked *a*, Fig. 4, shows three distinct strokes; discharge marked *b*, shows five; discharge *c*, shows two; discharge *e*, shows seven; discharge *f*, shows three; and discharge *g*, shows one. In this storm multiple strokes seem to have been the rule. Except for the records shown in Figs. 3 and 4, the films show mostly single strokes.

3. *Natural frequency.* In Fig. 4 the broken line of the discharge is made more evident by drawing definite ink lines at the side of the record for each half cycle where the record was sufficiently distinct to be definite. This is done lest the markings be lost in the reproducing processes. The accuracy of measurement is not high, so the frequencies recorded are divided into eight groups as follows: one stroke of no oscillation, Fig. 5; one stroke at 840 cycles per second; eight strokes at about 1400; six strokes at about 2000; two strokes at about 2500; twenty strokes at about 3000; and one stroke at 4000 cycles per second.

A careful inspection of the records brings out irregularities in the time between half cycles of some of the records, especially at the beginning of the discharge. This might be expected from the theory, but the constancy and regularity of the discharge of the line to earth at about 3000 cycles is surprising. A tentative explanation of the phenomena is herewith given: out some distance on the line a storm cloud hovered and induced a charge on the line which leaked over the insulators. The induced charge may have covered a mile or more of the line and may have been located at any point between the middle and end. The cloud discharged and freed the induced charge. The charge immediately tried to spread over the entire line. Apparently there was considerable dissipation of energy in the earth resistance. The first effect, usually, is a static wave of potential which reaches the end of the line where the instrument is placed, jumps the two series gaps of the instrument to the earth, pours out the entire charge to earth, overshoots the zero potential, and leaves the line oppositely charged. The gap sparks again and the potential again overshoots the zero and again the charge of the original sign covers the line. During each oscillation the current passes through the resistance of the earth, line, and spark, which uses up the energy. Finally, after a few half cycles, the potential can no longer jump the gaps to ground and the remaining charge finally settles down evenly distributed over the whole line.

Theoretically, the location of the freed charge on the line relative to the ends should make a difference in the rate of discharge to ground. Since one end of the line is insulated, the part of the charge which travels to this end should be reflected back to the discharging end after that end has begun to discharge. This should change the regularity of the discharge, more or less, according to the location and length of line covered by the original charge. In confirmation of this

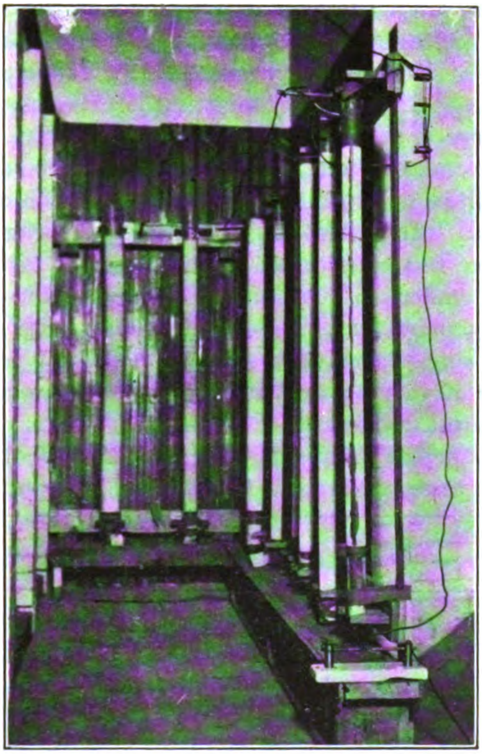


FIG. 9.—High frequency recorder as installed in the high-tension gallery of the sub-station

theory several records show an irregular spacing and minor peaks of current at the beginning; after a few half cycles, however, the effect of these reflected waves disappears and the line seems to oscillate as a whole. It may be noted here that the number of half waves in the record furnishes a means of estimating the minimum potential that the initial charge might have had.

4. *Very high frequencies.* In Figs. 3 and 4 the discharge was analyzed into waves having a frequency of the order of the period of the line. The next step is to analyze the harmonics in each of the waves. There may be two explanations of the presence of the higher frequency: either the cloud lightning may discharge with a frequency of the order of one million cycles per second, or the traveling wave along the line may meet with inequalities of capacity and induction which cause ripples in the waves. To detect these waves a recording high frequency meter was constructed. The meter as installed in the high-tension gallery of the Silverton sub-station is shown in Fig. 9. It consists of nine vertical coils of wire each closely wound in a single layer on a glass tube. The glass tubes and the wire are of varying sizes so as to give each one a different value of natural frequency.

The fundamental frequency and frequencies of the higher harmonics of each coil are given in the following table.

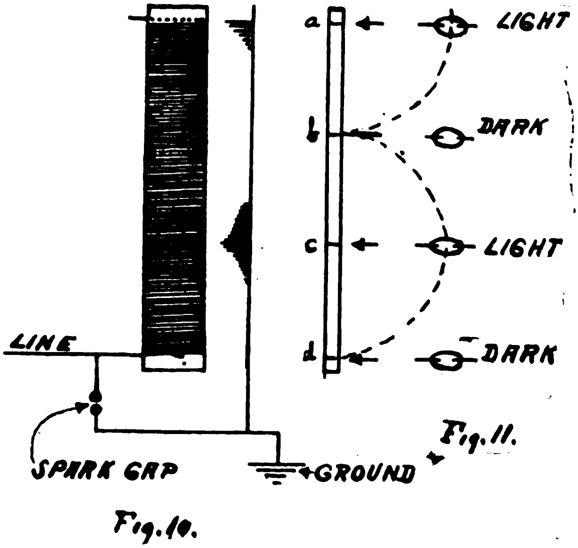
Coil No.	Fundamental frequency	Third	Fifth	Seventh
1	120,000	360,000	600,000	840,000
2	175,000	525,000	875,000	1,225,000
3	232,000	696,000	1,160,000	1,624,000
4	290,000	870,000	1,450,000	2,030,000
5	364,000	1,092,000	1,820,000	2,548,000
6	593,000	1,779,000	2,965,000	4,151,000
7	721,000	2,163,000	3,605,000	
8	890,000	2,670,000		
9	1,130,000	3,390,000		

Some of these values overlap and give a check on the results; for example, the third harmonic of tube No. 5 almost coincides with the fifth harmonic of tube No. 3.

The high-frequency instrument utilizes the principle of the stationary wave. One coil of the meter is represented diagrammatically in Fig. 10.

Parallel to the tube is an antenna toward which the brush discharge takes place. The tube is represented as receiving an oscillation which is three times its natural frequency of vibration. This is indicated by the two patches of brush discharge.

Fig. 11 shows the distribution of potential along the tube. An electrical wave passes up the tube to the dead end *a*, is reflected back, and meets the adjacent incoming wave moving in the opposite direction. When the waves cross each other at *b*, they have opposite potentials and neutralize each other. When the first reflected wave arrives at *c*, it crosses the peak of the next wave when both waves have the same sign of potential. The result is double the potential of one wave. Since, if the tube is in tune, all incoming and reflected waves cross each other at the same point, stationary waves are produced on the tube. The presence of these stationary waves can be shown by holding a small vacuum tube near the coil, Fig. 11. This much has been used by wireless telegraph engineers in conjunction with a capacity which can be varied to resonate the tube to the oft-repeated waves from a wireless sender. No such adjustment can be made in studying lightning, as the discharge comes in without warning, is usually over in one thousandth of a



Figs. 10 and 11.—Diagrammatic sketches showing the principle of operation of a high-frequency recording unit second, and does not repeat itself. An automatic recording device was found in employing a long photographic film in the static field between the tube and antenna, Fig. 10. The location of the film had much to do with the success of the results.

The conditions of the operation of the instrument may be explained by their analogy to musical resonance.

a. If a piano is pedaled to free the strings from their individual dampers, and a note is sounded on a cornet at some distance, the string on the piano corresponding to the tone of the cornet will be set in vibration and can be heard after the cornet note is stopped.

b. If the pitch on the two instruments is not quite identical, the string will respond with less vibration. If the pitch of the cornet falls midway between two adjacent wires both wires can be made to respond to a slight extent.

c. If the cornet is blown loudly near the piano the violence of the vibration will set in movement nearly all of the wires.

Corresponding to the conditions of the musical analogy, the high frequency instrument cannot, without precaution, be used to measure the harmonics of a lower frequency, say 3000 cycles, unless these harmonics greatly predominate over the fundamental. In consequence, the high frequency of the usual discharge coming from a distance out on the line as shown by most of the records of the duration apparatus did not give a record. The fundamental charge of low frequency travels along the coil, and its potential is so much greater than the potential of the higher frequency that it blackens the film over its entire length. If, however, a cloud just over the instrument is discharging at a high frequency, this high frequency potential will be forced onto the line and may affect the instrument.

If the difference of potential of the fundamental wave is limited to a small value by using a spark gap, the harmonics become relatively more effective. Due to the unpropitious conditions on the line, adjustments, and lack of facilities, only two of the records were of value.*

The high frequency recorder is better adapted to the study of cloud lightning directly. The receiving antenna can be made with a large coefficient of damping so that sensibly nothing but the forced oscillations will affect the film, and furthermore, local sparks can be eliminated.

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* The entire credit for the measurements obtained are due Mr. Peek for his painstaking and tireless efforts.

Quantity of electricity. Fuses have been used to indicate the relative severity of a lightning stroke, but a fuse in itself gives no absolute information regarding the quantity of electricity in a lightning stroke. The factor of duration enters, and this depends on the damping effects of resistance, various losses during the discharge, and the initial lightning potential. A small quantity of electricity oscillating for a long time may blow a fuse, while a hundred times as much discharging through a damped circuit might leave it intact.

The essential features of the apparatus for measuring quantity are a fuse that just blows and a duration apparatus that records the number of oscillations through the fuse. If the refinement of taking the logarithmic decrement into account is neglected for the moment, the equation for quantity is simple.

Let Q be the total quantity passing through the fuse (some multiple of the quantity freed on the line),
I the average effective current,
t the total duration of the stroke,
n the number of half-cycles of discharge,
J the joules of energy to raise one centimeter of the fuse to its melting temperature,
R the resistance of the fuse per centimeter length,
$T\phi$ the rise of temperature, centigrade, to melt the fuse,
w the weight of the fuse per centimeter length in grams,
S the mean specific heat of the fuse metal.

Then

$$J = I^2 R t = \frac{Q^2 R}{t}, \quad Q = \sqrt{\frac{J t}{R}}$$

In which $J = T \times w \times S \times 2.4$, and lightning $(q) = \frac{Q}{n}$

Nothing but approximations are necessary in these calculations, therefore the heat radiated from the fuse during the brief period of the discharge is neglected or rather allowed for by choosing, for calculation, the size of fuse one above the fuse melted out. The larger the fuse that is blown the less the relative value of radiation, because the surface relative to the volume is also less. Our interest in the quantity of electricity in the lightning stroke increases as the quantity becomes greater, and fortunately, for the upper value, the accuracy correspondingly increases. Other things being constant, it requires a fuse of four times the weight to hold a charge of twice the quantity.

There may be a fraction of the original quantity left on the line after the discharge has passed due either to a gap in the circuit or to the gap of the fuse that blows. This residual quantity has nothing to do directly with the result because there has been already more than one oscillation. Its indirect bearing is beneficial if approximate calculations are being made. The fewer the oscillations recorded the nearer is the average quantity to the original maximum quantity set free on the line.

The arrangement of the apparatus for measuring the quantity of electricity is shown in Fig. 12. A duration recorder is shown in series with three magazines of fuses. Each magazine of fuses consists of a set of parallel fuse wires placed one above the other. At one end they are connected to a vertical post of some insulating material and at the other to a metallic post. In front of this fence of fuse wires is a vertical post carrying a hinged arm which rests on the top wire. As each fuse blows the arm drops automatically on the next fuse below. All the fuses in one magazine are the same size but the fuses are graded in size in the separate magazines. In operation the arc will hold in the vapor of the small fuse while a larger one melts. For this reason a metal of good arcing quality, like lead for example, is preferable.

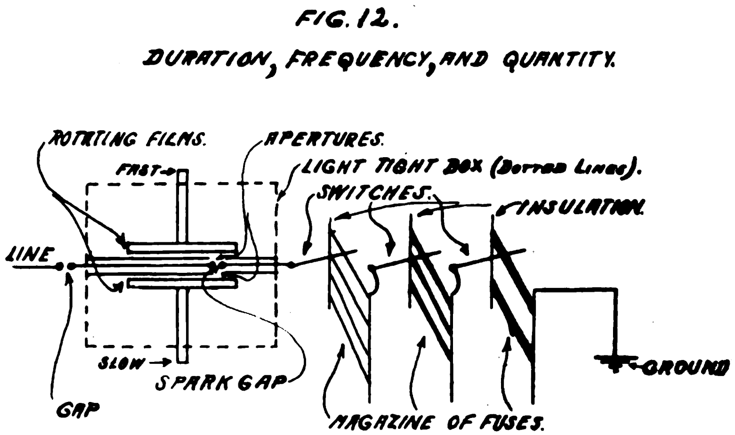


FIG. 12.—Combined apparatus for measuring duration, frequency, and quantity of electricity

Another method of making the calculations for quantity of electricity is by calibration of the fuses using an oscillograph to measure current and time. Using a voltage too low to maintain an arc, currents of increasing values with the same size fuse are used and a curve made between the factors of current and time. For very short intervals of time the equation seems to show independence of the radiation and is:

$$I^2 R t = \text{constant}, \qquad \text{or } I^2 t = k$$

Using the data taken from one of the tests, which was a heavier stroke than the average but not so severe as some others, a value of 0.032 coulombs was found for the total quantity that passed. It happened that multiple strokes occurred each time a fuse test was made, so a near approximation of the quantity of lightning induced by the cloud cannot be made on account of the radiation during the interval of the multiple strokes. A rough approximation of the quantity in this case is 0.003 coulombs. If this quantity of electricity was spread over a mile of line having a capacity between line and ground of 0.01 microfarads, the initially impressed voltage would be about 600,000 volts. The question whether a voltage of this nature will jump an insulator or not, is not solved by impressing a constant voltage of the same value on the insulator to determine if it will spark over, but it is entirely a matter of the relation of the dielectric-spark-lag of the insulator to the time constant of the line wire. The inductance of the line opposes momentarily the spreading of the charge over the entire line. A wooden cross-arm gives a much greater dielectric-spark-lag than an iron cross-arm. This subject is treated experimentally later under its appropriate head.

A refinement in the calculation of quantity requires the integration of the instantaneous value of current over the duration of the discharge.

$$Q = \int i \, d t$$

in which i may have the approximate form

$$i = k_1 \varepsilon^{-\frac{Rt}{2L}} \sin k_2 t.$$

Quantity meter of ballistic principle. Instead of using fuses, which are destroyed and have to be replaced, an ordinary hot-wire ammeter may be used if it is properly calibrated and the hot wire sufficiently insulated so that the drop of potential due both to $I R$ and $L \omega$ do not cause a short circuit. In the laboratory this method is convenient but in the study of cloud lightning effects the hot-wire ammeter has the disadvantage of leaving no record and therefore requires constant watching and patient waiting.

If quantity and frequency are known, this method can be used to measure duration or number of cycles.

Movement of charges on parallel wires. It is seen from the low frequency of the discharges of Figs. 3 and 4 that the concentrated charge under a cloud flattens out over the line when set free. The free movement of the wave seems to be greatly retarded by the surface resistance of the earth directly under the line wire. Incidentally it may be noted that a short line will be harder hit than a long one by the same cloud conditions, although, by the law of chance, not so often.

FIG. 13.

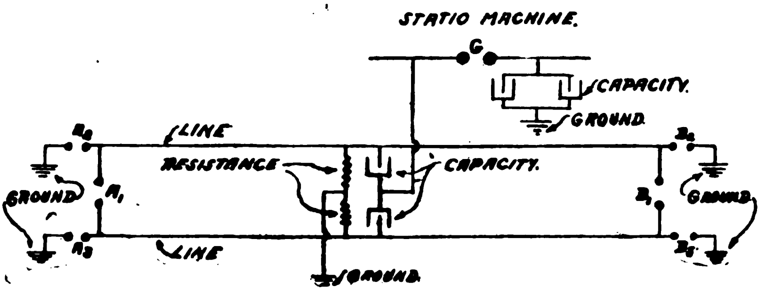


FIG. 13.—Laboratory test illustrating the mutual induction between two moving lightning charges

There is another phenomenon observed which modifies somewhat the potential of the traveling wave. This was first observed on a two wire circuit. When equal induced lightning charges on the two parallel wires are freed, electro-magnetic induction will oppose the flow in the same direction. With a fixed length of gap at each end in each wire of a two wire circuit, only one gap would spark unless the discharge was either unusually heavy or quite near the station. This same phenomenon was checked up in the laboratory on a circuit represented in Fig. 13.

The first test utilized the gaps A_1 and B_1 only. When properly adjusted, both of these gaps sparked simultaneously. The second test utilized the gaps A_2, A_3, B_2 and B_3. Under certain conditions of test the wires would spark to earth invariably at opposite ends. These tests seem conclusive of the tendency of the mutual inductance to force the equal charges in the opposite direction along the circuit. Line to line discharges due to cloud lightning sometimes take place. The above phenomenon no doubt is partially the cause of such discharges.

A brief description of the two lines on which observations were made follows.

The Pueblo and Suburban Light and Power Co. The Pueblo and Suburban Light and Power Co. has 24,000-volt lines between Pueblo and Victor (altitude 10,000 ft.), Colorado. The power house is at Skaguay, somewhat lower than the Victor substation. General observations only were made here. The measuring instruments did not arrive until the beginning of August and work was then taken up on the Animas Power and Water Co's. lines as the storms were more frequent in that locality in the late summer. All the new measurements were made on the line during the latter part of August, 1907.

The Animas Power & Water Co. The Animas Power & Water Co. transmits energy from the power house (8,000 ft. altitude) to the sub-station (9,500 ft.) at 43,500 volts, with the neutral grounded at the power house. There are two separate lines, one at the bottom of the cañon to minimize the electrical disturbances in summer, and the other carried directly up 1000 ft. to an elevated plateau to minimize the trouble due to snow slides in the winter.

At the main substation, the voltage step downs to 17,000 volts delta. On the 17,000-volt system there is one customer's station (100 kw. capacity) with grounded neutral; but this seems to have no beneficial effect when recurring surges play over the system.

On the system are about 30 customer's stations, all mines or mills except the city circuit of Silverton. The lines run along the cañons, up the gulches to the mines, and over the ridges. In two places the lines reach an altitude of over 13,200 ft. The difference in altitude is about 4000 ft. on the 17,000-volt system, and 5200 ft. on the entire system. The system covers a lightning area estimated at 270 square miles. The 17,000-volt circuit is not in duplicate. The feeders have sectionalizing switches at several points. At the mines, the potential is transformed to 440 volts and, in several places, is carried overhead for several hundred yards to different tunnels.

The severity and frequency of lightning storms during the season has been previously noted. Two storms often occur in one day. Storms sometimes hover over some part of the system for 24 hours. In that neighborhood it seems that the cool winds from the north meet the warm winds from the stretches of desert to the south. It is probable that the problem of lightning protection here is as difficult as any place in the world.

Some of the methods and instruments for measuring lightning potential, frequency, duration and quantity have already been described. A most valuable aid was a lightning recorder—a development of the tell-tale paper.

Lightning recorder. One of the types of lightning recorder used consisted of a cylinder, uniformly rotated by geared power, carrying a ribbon of paper, Fig. 14. Four electrodes pointing toward the axis of this cylinder and separated from the circumference by clearance only, were connected to the lightning-arrester. This recorder was placed at the neutral or multiplex connection of the arrester having one electrode connected to each phase and one to the ground. This arrangement differentiates between line to line, and line to ground discharges. A single-phase induction motor was used for power in the first set of instruments. This power was carried through multiple gears which permitted of four speeds in multiples of tens. Most of the records were taken with a speed of about 0.1 in. per second. Later designs of recorders using clock work have the advantage of greater uniformity of speed and independence of the voltage and frequency of the circuit.

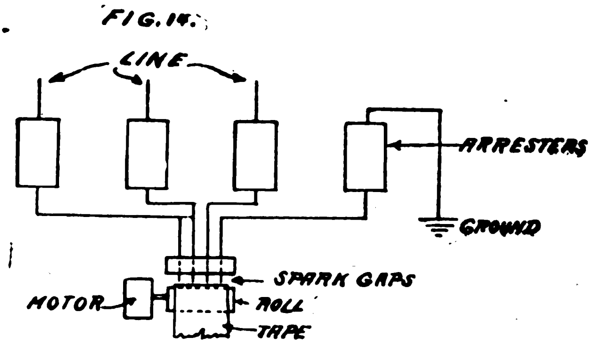


FIG. 14.—Lightning recorder to show the discharges through a lightning-arrester

The records show the exact time and phase of the discharge, and, by the size of the punctured hole, give an indication of the relative quantity of electricity discharged. If, however, the arrester is connected to a circuit supplied with power, the dynamic current will burn away all trace of the original hole produced by the static discharge. When a phase is accidentally grounded, the record tape shows which phase is producing the surges and how long the trouble lasts.

Lightning discharge records. Some typical and unusual records of lightning discharges from lines are herewith reproduced. Fig. 16 is the record of an aluminum arrester taking a recurrent surge due to an arcing ground to the third phase. After 2 seconds of heavy discharge the trouble nearly cleared itself but it was 25 seconds before the surges were entirely over.

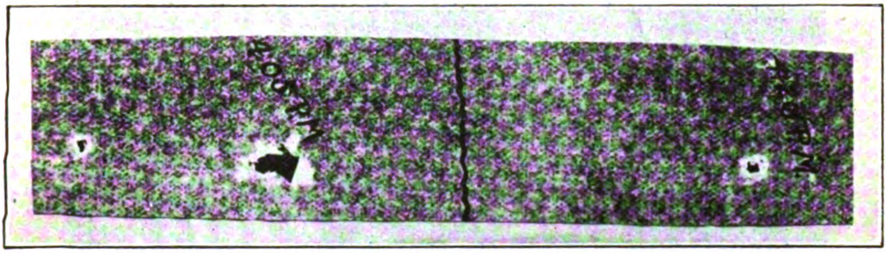
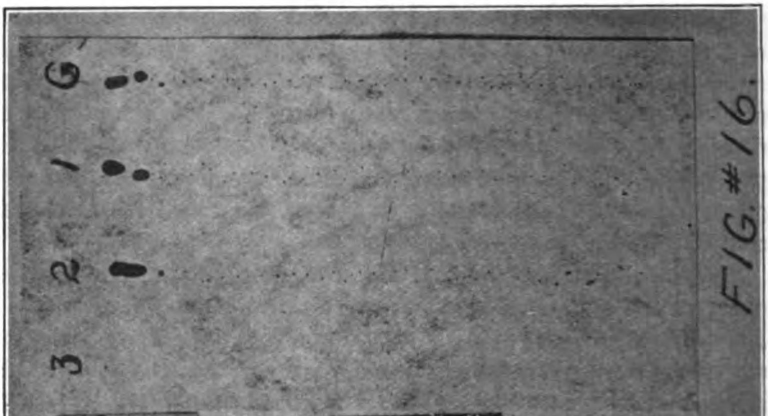
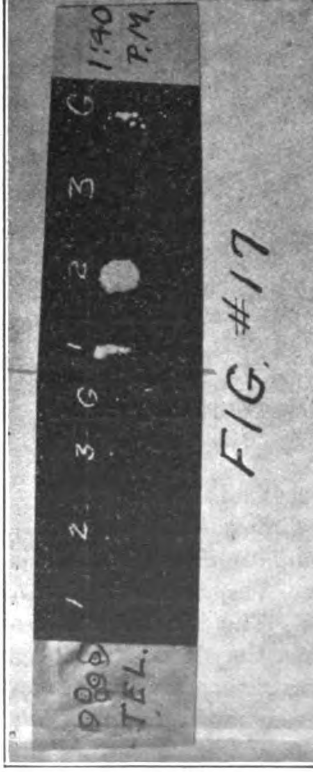


FIG. 15.—Three discharges of lightning through a cone-type aluminum arrester on an idle line. The central hole is the largest recorded, due entirely to static, during the season. The discharge caused a loud report

Fig. 17 shows three simultaneous records; to the left is a record of 4 multiple strokes on the telephone circuit, in the middle the discharge of an aluminum arrester, and to the right the discharge of a liquid-electrode arrester. The telephone record shows tiny holes encircled by ink rings. This is a static hole of usual size on the telephone circuit when the storm is over five miles distant. The aluminum arrester record shows a somewhat larger hole which was enlarged by the dynamic current. The liquid-electrode arrester record shows large holes burned by the dynamic current and shows furthermore that the four discharges were so close together that the holes burned into one. Phase three, with the same single gap setting, did not spark. The aluminum arrester was inside the choke-coils and only one of the four discharges passed through the choke-coil. It should be





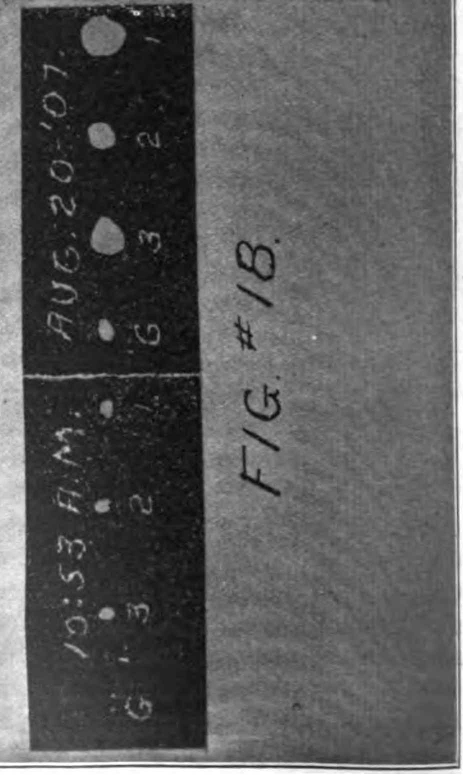


FIG. 16.—Discharge of continuous lightning through an aluminum arrester. There was an arcing ground in phase 3. Phase 3, shows an initial discharge only. Phases 2 and 1 discharged heavily to ground during 3 seconds, then the ground began to clear itself. The total time of discharge was 40 sec. The records of longer discharges cannot conveniently be reproduced here

FIG. 17.—Three simultaneous records. To the left, the telephone arrester shows multiple strokes; in the middle, the aluminum arrester shows a single discharge; and to the right, the record of the multiple discharges of phases 1 and 2 to ground through the liquid electrode arrester.

FIG. 18.—Two simultaneous records of discharges through liquid-electrode arresters

noted that these four distinct discharges gave the effect on the arrester of a continuous discharge about one second long.

Fig. 18 shows two discharges of the liquid-electrode arrester. These discharges were normal. These arresters were on different feeders and discharged simultaneously.

Fig. 15. This record is most unusual and remarkable. This tell-tale paper was in the gap between a cone-aluminum arrester and ground on a 24,000-volt line without dynamic potential. The static discharge usually makes a very small hole. The static discharge which punctured the middle hole made a loud report. This was the heaviest discharge recorded during the season. It produced no effect on the aluminum arrester.

Lightning alarms. Since the aluminum arrester is designed to operate continuously for a half hour or more, an alarm may be attached to all these arresters, so that an operator in his office may know when the arrester discharges. He can begin to take precautions to clear the line if the trouble is continuous.

As a convenience in the Colorado tests, Mr. Peek arranged a lightning alarm on the principle of a wireless telegraph receiver which would ring a bell for cloud lightning, or grounded phase, when such occurred on any part of the system.

Equipment for study in the main sub-station of the Animas Co.

1 High frequency recorder on 43,500-volt dead line.

1 Duration meter and low frequency meter on 43,500-volt dead line.

3 Lightning discharge recorders on three telephone circuits.

2 Lightning discharge recorders on 17,000-volt liquid electrode arresters, outside of choke-coil.

1 Lightning discharge recorder on 17,000-volt aluminum cell arrester, on bus-bars.

1 Lightning potential recorder on 17,000-volt line.

1 Lightning alarm (general).

1 Quantity recorder on three telephone circuits.

1 Quantity recorder on 43,500-volt dead line.

To show if discharges were not taken by lightning-arresters, the following device was used:

In the customer's stations, all points of the line which had less insulation than the main line—for example, leads from oil switches and transformer bushings—were wrapped with white paper tape or covered with sheets of paper. Only a few of the customer's stations had lightning-arresters installed. It was vital to locate the trouble. There was no indication in the main station, except the action of the circuit breakers from the resulting short-circuits. Subsequently, the short-circuits could be located by means of the arc marks on the tell-tale papers. Cloud lightning caused several short circuits during the season but in no case did such trouble, due to cloud lightning, occur at stations protected by arresters. Although the two customer's stations giving the most trouble were only two and three miles from the sub-station, a gap of 0.4 in. between line and ground at the main sub-station would not spark over although the spark would jump 3.5 in. and more at the customer's sub-station. This is direct proof that the peak value of lightning potential is much higher at the point on the line nearest the cloud than elsewhere, and rapidly diminishes as the charge travels along the line, dragging its complementary opposite charge along the high resistance of the surface of the earth.

Notes on choke-coils. Twice during the tests the lightning choke-coils showed very materially their beneficial effect. On the line side of the choke-coils an arrester with a single gap length of about 1 in. was installed and another arrester with a gap length of about 0.5 in. on the station side, on the bus-bars. Two discharges occurred over the 1 in. gap which did not discharge over the 0.5 in. gap in spite of its lower sparking potential. The conclusion from the experience is that the discharge must have been of both high frequency and high potential and furthermore that the arrester discharged the lightning before the charge could pass through the standard lightning choke-coil.

That many discharges passed through the choke-coils to the 0.5 in. gap may be due to the conditions of lightning potential and frequency. If a lightning potential in the neighborhood of 1 in. gap equivalent and of moderately high frequency came into the station the choke-coil would allow the potential of the bus-bars to build up to a potential equivalent to 0.5 in. and then start the discharge over the arrester connected to the bus-bars. The aim in the design of choke-coils is to make them just large enough so that if the frequency of the discharge is not sufficient to pile up the potential in front of the choke-coil it is not high enough to injure the end turns of the transformer.

Once during the season a phenomenon occurred which seems to bear out further the experience of the laboratory that a choke-coil may, under certain circumstances, cause a longer spark after the discharge passes through it than it will on the line side.

The laboratory tests were described by the writer in the discussion at Niagara Falls last year. The equivalent effect occurred on the line. From the main sub-station two lines ran south and one north. Each carried a telephone circuit. The lightning recorder on the southern telephone circuits recorded a lightning stroke to the south but the lightning-arrester on the north power line discharged, although its single gap was approximately the same as the arrester on the south power line. In other words, the lightning seems to have passed through a choke-coil to the bus-bars and back through another choke-coil to the north arrester. The hole in the paper punctured by the static on the telephone lines indicated a discharge of medium quantity only. This experience carries only its face value and is not sufficient to be the basis of definite conclusion. A method will be outlined later for studying the operation of choke-coils on transmission lines, looking toward the procuring of definite data.

Experiences with a grounded phase. Several times during the season a phase was accidentally grounded. Each time there was an arc to ground and vicious surges occurred on the lines. Some of these were extremely odd. A lightning stroke came into the main sub-station on the 43,500-volt line. The lightning-arresters were designed with permanent resistance in series limiting the current to about 6 amperes at double normal potential; consequently the discharge took place between a phase wire in the station and an iron girder, some 18 in. distant. This arc roared continuously during the entire trouble. The liquid-electrode arresters on the 17,000-volt circuit discharged continuously for several minutes but were finally disconnected by their fuses as they had reached their limit of endurance. A switch broke down at Camp Bird Mill, throwing a ground and short-circuit on the 17,000-volt circuit. An arc jumped from each of two phases downward and out about 16 in. to insulator caps and across between caps 20 in. making a total of 52 in. Subsequently the arc rose on each side to the ceiling girders making a total of 6 ft. Meanwhile all the iron pipes and rods in the building were alive with brush discharge. The static from the iron pipe, carrying the 110-volt lighting wires, discharged against the white brick wall so viciously as to leave a permanent dark streak. The 110-volt light cables were short-circuited by induced sparks from the arcs on the high tension circuits. A spark jumped several inches from a pipe to the iron rod actuating a 2300-volt oil switch. The trouble was removed by opening the switches at the power house. Except the oil switch at Camp Bird no apparatus was damaged.

This trouble arose from the lack of a good lightning-arrester for transitory lightning. The secondary trouble was due to the lack of an arrester that had a long endurance for continuous surges. The cone-type aluminum arrester was not installed until later. To any witness of these phenomena there can be no doubt that the discharging of these continual surges is the most difficult problem in lightning protection.

Another arcing ground. The Champion mine had no protective apparatus installed. A stroke of lightning came in and damaged a 17,000-volt transformer bushing. Subsequently this transformer was thrown back into service on the 17,000-volt circuit for a minute. It arced over its bushing to its case. The case was insulated from the earth by wooden supports. The lightning-arresters in the main station did not discharge. Later the switch was closed for a little longer period with the same result. A third time the switch was closed, the case began to arc to ground and the lightning-arresters began to discharge continuously at the substation until the transformer was again disconnected.

Subsequent arcing grounds. Later in the season a cone-type aluminum arrester was installed on the bus-bars of the 17,000-volt system. A grounded phase occurred twice after this arrester was installed. The arrester discharged continuously for over 15 minutes, and relieved the line, until the ground was removed.

Direct stroke. The writer had planned to make a direct study of cloud lightning but, due to the time absorbed by the measurements on the line and an accident, Fig. 6, it had to be postponed. Indirect studies were made both on the line and in the laboratory. There are no overhead grounded wires on the Animas system. So far as practicable the lines are run along the bottoms of the cañons and gulches. The mountain sides are steep and give some protection, no doubt, against induced static. At many points the lines run exposed up the sides and over the ranges but by the law of chance all these points were uninjured, so far as known, except one. This happened on the 43,500-volt line about a mile away from the power house. At the power house, this line rises abruptly 1000 feet and is carried along a high plateau. At the point struck, five poles were more or less splintered, although none was rendered unserviceable, and incidentally, no apparatus was lost in the power house. Splinters were thrown edgewise out of the surface of the poles to a distance of thirty feet. The hole or groove was often less than ¼ in. wide but 1 in. or more deep. Along the line, quite near, with their tops higher than the wires, were several trees. The question arises, why should the lightning choose a path through the high insulation of the poles rather than strike the tall sappy trees of greater conductivity? The reason for this differentiation may possibly be due to chance but it seems to lie in the conductivity of the horizontal line relative to that of the earth and tree. As further evidence of this, two direct strokes occurred in this neighborhood a year before which scarred the poles and there was no tree damaged near the line.

It may be imagined that when a charge on a cloud begins to concentrate in a discharge path, the corresponding induced charge on the earth concentrates under the same point.

The potential at the tree top depends directly on how much static electricity can get to it through the relatively high resistance of the tree and earth. Although the line is not connected to the ground, it holds a considerable charge due to gradual leakage as the cloud moves over the line. This charge can concentrate with no impedance but the inductance of the line, and due to this concentration the excessive displacement current on the line may swing the cloud discharge into this path. Once the lightning strikes the line, the potential builds up too rapidly to be released by spreading the charge over the line and consequently it takes the shortest single path or multiple paths down the poles. The laboratory tests bearing on this theory are given below.

Many of the strokes of cloud lightning observed were between clouds and not to earth.

Wooden versus metal cross-arms. Under the heading of lightning potential the question was raised " does series resistance affect the spark potential of a needle-gap?" The answer was, that it affected it only slightly if the resistance was not carried too high. With a discharge current of half an ampere, there is no great change in the spark potential even for suddenly applied potentials of high frequency. When, however, the resistance in series with a gap is greatly increased, the current necessary to charge the static of the needle points and furnish the energy for the brush discharge which precedes a spark, is retarded and an equal gap in parallel having no series resistance will take the spark.

The same phenomenon occurs on transmission lines in differentiating between wooden cross-arms and metal cross-arms. If the wood is dry there is no question but that the insulation between the two line wires is greatly increased. On the other hand, if the wood is wet and dusty the value of the wooden cross-arm is not so evident. The following experiments were made to show that on low frequency, say 60 cycles, the wet wood gives no better insulation than the metal, but at high frequencies it gives much better insulation. A wooden cross-arm was arranged as shown in Fig. 19: two porcelain tubes held wires 1.7 in. above

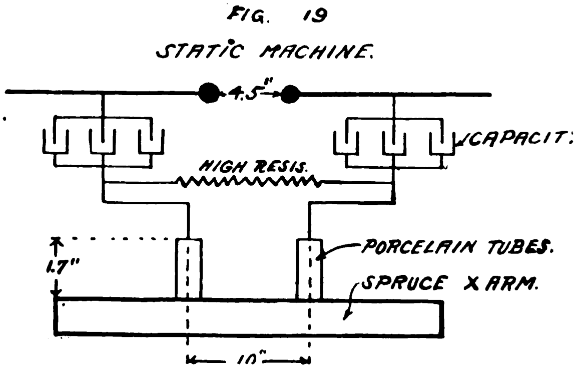


FIG. 19.—Diagram of connection for the laboratory test proving that the wooden cross-arm has great advantages over the iron cross-arm in resisting lightning strokes

the surface of the wood and 10 in. apart. On the upper surface of the wood tin foil or a wet towel was placed in imitation of line conditions. Fig. 19 shows the conditions of the second test. The first test was made on a 60-cycle circuit with a needle-gap in parallel with the cross-arm. The voltage breakdown was the same whether the wet cloth or the metal was used. By transformation, the voltage was 46,900 (eight readings) and by needle gap it was 3.5 in. (52,000 volts by interpolation from the curve). This higher indicated potential by the latter was due to local oscillations set up by corona discharges over the porcelain top. After the cloth had dried out somewhat the spark potential by transformation rose about 2 per cent.

The potential was then suddenly applied by means of the apparatus shown in Fig. 19. The frequency was 2.25 million cycles per second. The applied potential was a 4.5 in. gap between spheres 1.25 in. in diameter. The equivalent needle gap was 5.6 in. (68,000 volts) when the cloth was used very wet. The equivalent needle gap was only 2.5 in. (42,000 volts) when the metal plate was used between the porcelains. This disruptive voltage is even less than with the gradually applied potential. It results from the multigap effect of the metal plate. The plate has a static capacity which takes an appreciable charging current across the gaps. It is well to note that 5.6 in. was the limiting potential that the needle would spark over, so the actual conditions would have been even more favorable to the wet wood if the applied potential had been greater. Taking it as it was, the wet wooden cross-arm was 160 per cent. better than the metal as a protector against high frequency lightning and the metal cross-arm is only 80 to 90 per cent. as good for lightning as it is for generator potential.

Although these figures will, no doubt, be somewhat modified by changing the relative conditions of the test, it is safe to conclude that a wooden cross-arm is always to be recommended from the standpoint of insulation and would be a most desirable and economical feature even on iron towers. It is usually cheaper to add insulation with wooden cross-arms than it is to obtain it with added porcelain in the insulator. When the wooden cross-arms is only damp or dry it may add greatly to the insulation against lightning. These tests have a bearing on the use of insulator horn-gap protectors that will be apparent to the engineer.

GENERAL COMMENTS ON THE ARRESTER EQUIPMENT OF THE ANIMAS COMPANY

Last summer the equipment of arresters consisted of four 43,500-volt special multigap arresters using concentrated series resistance, four 17,000-volt multigap arresters using distributed series resistance, and five liquid-electrode arresters. Two of the 17,000-volt arresters were rendered inoperative by having two liquid-electrode arresters installed in parallel. The liquid electrodes invariably took the heavy discharges. The following brief comments are made on the operation of the arresters during the season:

The series resistance in the high-tension arrester was of such value as to limit the dynamic current flow to six amperes at double normal voltage. The lightning strokes in this district were much too severe to be discharged at this limiting discharge rate, consequently three times during the season discharges took place between the station wiring and the girders, jumping 18 in. or more to ground. The 17,000-volt arresters with the series resistance limited the current discharge to 12 amperes, and usually were able to take the discharges. In one noteworthy exception, an arc took place between a lead-in wire and the ground. The liquid-electrode arrester on the 17,000-volt circuit gave satisfactory operation in all cases of transitory lightning, but during grounded-phase conditions the arrester continued to operate for some minutes until it was somewhat damaged. These arresters are not designed satisfactorily to take care of continual lightning, although they have an endurance that is several hundred or thousand times the endurance of the multigap arrester. If the entire system had had adequate protection against transitory lightning there would have been no trouble with recurrent surges, with but one exception—a direct stroke on the high-tension line. Since there are more than thirty points to be protected on the 17,000-volt system and only seven points protected, recurrent surges from failure of insulation at the unprotected stations occurred several times during the season and interruptions were caused by short-circuits as the result of sparks at unprotected stations. Additional arresters for the system were on order but arrived too late to be installed for the season of 1907.

The full protection of the system involves: first, the installation of one liquid-electrode arrester at the power house on 43,500 volts; secondly, one gap-aluminum arrester at the sub-station on the bus-bars, 43,500 volts; thirdly, three additional liquid-electrode arresters on the 17,000-volt circuit; fourthly, ten additional aluminum arresters on the 17,000-volt circuit; and, fifthly, completion by installation of reconstructed multigap arrester. The units of the multigap arrester formerly on the 43,500-volt circuits were utilized in the special design of arresters for the 17,000-volt circuit. By this change practically no money was lost in the lightning-arrester investment.

Location of arresters. The object to be obtained in the location of arresters to the best advantage is as follows:

Aluminum arresters should be distributed as uniformly as possible over the system, choosing the more important stations where there is an actual attendant, or one in the near neighborhood. These arresters should have their series gaps set at a comparatively low value in order to take care of recurrent surges from an accidentally grounded phase. The liquid electrode and multigap arresters at adjacent stations will require a higher abnormal potential to start the discharge and by proper proportioning should be protected against recurrent surges by the adjacent aluminum arresters. Recurrent surges have, in general, lower frequency than lightning from induced clouds and are not so much localized. Therefore the lightning-arrester designed for transitory lightning should discharge any induced cloud effects in its locality, but should pass on recurrent surges to the nearest aluminum arrester. In stations where there is no attendant, and none available within five minutes' call, the setting of the gap of the aluminum arrester should be such as to make its action transitory, except for exceedingly bad local conditions. In the main sub-station the aluminum arrester should have a gap setting only slightly above line potential with the object of making these arresters discharge, as far as possible, continuous lightning from outside points on the line. The object of this is twofold; first, to keep the line potential down; secondly, to draw the attention of the attendant to the fact that there is trouble on the line which must be located and corrected.

Since the aluminum arrester is designed to have a duration of discharge of a half-hour or more, this should give sufficient time to locate the particular circuit on which the trouble occurs and make the necessary switching without disturbing the rest of the system. It is evidently inadvisable to have any unattended aluminum arrester discharging surges which do not make themselves known to the station attendant, because the result would be final disconnection of the aluminum arrester from the circuit by the blowing of its series fuse, thus leaving the station without any protection whatsoever. After such an arrester is disconnected the surges will be carried on to the next arrester or into the sub-station. In localities where there are two or more stations near each other an endeavor should always be made to utilize a multigap arrester at one, and either an aluminum or liquid-electrode at the other. In this way even the multigap arrester of low discharge rate could be utilized, since the adjacent arrester of large discharge rate would assist in discharging the cloud lightning.

Characteristics of the gap-aluminum arrester (*concentric cone type*). *First.* The general characteristics of the aluminum cell with a definite limiting voltage, above which the current flows through freely, are known. At voltages above the critical value the film has no resistance and the only resistance in the circuit is the internal resistance of the electrolyte. In consequence of this characteristic the discharge rate at double normal voltage can be made as high as desirable.

Secondly. When the aluminum plate with its film-coated surface stands in the electrolyte, the film dissolves more or less rapidly according to the nature of the electrolyte. This dissolution can be made very small or considerable by the choice of the electrolyte.

The *third* feature in regard to the arrester is its endurance to continual lightning. The chief obstacle to the length of endurance is the same as in all other electrical apparatus; namely, heating; the arrester can be made to endure from a minute up to six months or longer by appropriate designs.

The *fourth* factor in the design of the arrester is its total life. The arrester should be given a life of several years. This is influenced by the nature of the electrolyte as well as the number of times and duration of the discharge.

The *fifth* factor entering into the design of the arrester is the cost. The four other factors can be made as nearly perfect as desired, but with the limiting value of cost the three first named factors are somewhat at variance with each other; for example, with the same arrester it is possible to give high current discharge rate and low dissolution of film, but in so doing the duration of the discharge will be diminished. On the other hand, the duration of discharge and the low value of dissolution of the film may be maintained, but the high rate of discharge sacrificed somewhat. In designing arresters the aim has been, in general, to meet the specific conditions imposed by recurrent surges on a system.

Until the development of the aluminum arrester there was no arrester which would take care of recurrent surges. This condition was one of the justifications for the use of a grounded neutral system. To meet the condition of recurrent surges requires a lightning-arrester that will discharge these surges for a time long enough for switching to be carried out to isolate the circuit on which the trouble takes place; meantime a repair man can be well on the way to the point where the damage has been done. A half-hour or an hour would usually be sufficient to do this. Therefore in the general design of the arrester to take care of recurrent surges the parts should be so proportioned as to give, first of all, the duration of discharge; secondly, the parts should be so proportioned as to give a discharge rate high enough to take care of any kind of induced or internal lightning. The value of this discharge rate is 1000 amperes at double voltage, correspondingly higher at triple voltage, and discharges all the way from 125 per cent. abnormal voltage, where the spark takes place, up to the highest voltage reached. In order to get this favorable condition, an electrolyte is chosen which is not the most favorable from the standpoint of dissolution of film; consequently in this arrester it becomes advisable to connect it occasionally to the circuit. In this matter there is a wide latitude of time; for example, it may be daily, or weekly, or even longer under the usual conditions of temperature. It has been found advisable, not only from the standpoint of the condition of the arrester, but also from the standpoint of the education of the operators, to recommend that these arresters be connected to the circuit at least once a day. To the writer's knowledge circuits have been shut down because the operator became frightened at the continuous discharge of the lightning-arrester when trouble occurred on the circuit. When continuous lightning occurs on the circuit it is desirable to have as long a duration of discharge of the arrester as possible. If the arrester has not been connected to the circuit for some time there is an initial rush of current which, although doing no harm to the arrester, warms it up unnecessarily and thereby shortens the possible time which the arrester would have operated had the film been in prime condition at the start. The wear due to this daily testing of the arrester is inappreciable and the time of the attendant is valuably spent.

When the aluminum arrester is to be used as a line arrester or in isolated stations where it is desired to take care of transitory lightning only it is necessary to make but two changes; first, a change in electrolyte to give less dissolution of film; secondly, as stated previously, the length of horn gap in series should be set at a value that will not be affected by the numerous surges of harmless abnormal potential which occur on transmission systems. Since the ordinary lightning-arrester does not begin to operate until at least double voltage is reached, and since practically all apparatus is tested at double voltage, it should be recommended that the gap of the line arrester be placed at not less than double voltage. It should be noted that if the arrester gives an initial current rush after being off the circuit for a long time, no harm will be done unless such initial rush of current should throw the circuit-breaker at the station. The slight amount of heating that occurs from this initial rush, lasting for not more than a very few cycles, and usually not more than one cycle, is negligible in the aluminum arrester used as a transitory lightning-arrester. This arrester may be allowed to stand for long intervals without connection to the line.

By sacrificing the duration of discharge, the arrester can be given a discharge rate of 2000 amperes at double normal voltage, simply by an increase in the amount of the electrolyte in the same set of aluminum cones.

To facilitate the testing of the aluminum arrester, the horn gaps are made in special form to act in three capacities: first, as a horn gap; secondly, as a short-circuiting switch to the gap, and thirdly, as a disconnecting switch.

SOME AUXILIARIES TO THE GAP-ALUMINUM ARRESTER

The lightning alarm and the fuse. Since the duration of this type of aluminum arrester is limited, it is necessary to take steps to remove the trouble as soon after it occurs as possible. This arrester may be located either in-doors or out-doors; and in order to make sure that the operator's attention will be called to the condition of discharge, an extra cell is placed in the arrester circuit near the ground and leads are carried from there to the office of the attendant or the superintendent. This bell begins to ring as soon as the discharge takes place over the arrester and continues to ring until the arrester ceases to discharge.

The arrester has a definite endurance to the discharge. Actual tests have been carried on to determine the life of a 13,000-volt arrester under different conditions. The arrester was caused to discharge in relays of two or three hours twice a day until the total time was 80 hours. The arrester was then dis-assembled and it was found that the plates were somewhat worn but the arrester was still in good condition. If the duration of each relay had been less than two hours, the wear of the arrester would have been very much less. It is estimated, however, that the summation of the total time of grounded phases on a system would hardly reach the value of eighty hours in many years.

Series fuses in each leg are introduced to meet two conditions. First, if for any reason the dynamic potential should be increased to a dangerous value, the arrester will discharge these heavy currents continuously until disconnected from the circuit. It is evidently impossible to use these lightning-arresters to discharge high dynamic current for any great length of time. Under normal conditions the dynamic current reaches a value of 0.4 ampere on 25 cycles, and 1.0 ampere on 60 cycles. Any current above these values is current coming from lightning surges. This current does not represent directly an energy loss because the aluminum cell is a fairly efficient condenser and the power-factor is correspondingly low. When, however, the dynamic current for any untoward reason rises above the critical film voltage the current is entirely energy current and the internal loss considerable. In this discussion only energy from the generator is being considered, and it is evident to any operator that if the potential on his line rises to such an abnormal value for any length of time all the lights on the system will be burned out and the motors be operated under abnormal conditions. The second condition which may arise to necessitate the disconnecting of the arrester from the circuit will be that due to the length of time the arrester is discharging more than that recommended as the limit. It may be noted, although the time recommended is only a half hour or a little greater for duration of discharge, in actual practice, the arrester has been caused to discharge repeatedly for two or three hours at a time. If one of these arresters is placed on the circuit and left there the discharge rate remains about 1.0 ampere until the arrester reaches the limit of its endurance. This as already stated depends upon the heating. The current rises rapidly and if the arrester is not disconnected, one cell after another will short-circuit, throwing each time the extra potential on the other cells until finally the condition of total short-circuit is reached. These arcs will tear holes in the aluminum and will reduce the stack of cones to their scrap value. If, however, a fuse of size amply large enough to take any induced stroke of lightning be placed in series, the fuse will still be small enough to disconnect the arrester from the circuit in time to save it for future use. In either event, whether the arrester is disconnected by the fuse or is destroyed by dynamic current, this point of the system is left without protection, but by the use of a fuse the arrester in test has been put back into the circuit again with no material damage other than the natural wear due to the passage of current.

This matter of the use of a fuse in connection with the gap-aluminum arrester has been treated at some length in order to show the difference in this practise between the application to the aluminum arrester and the multigap arrester. There are some justifiable objections to a series fuse with the multigap arrester which do not apply to the aluminum arrester.

Aluminum arresters for direct currents. These arresters are applicable to pressures from 110 to 1200 volts. The form of the arrester differs from the gap-aluminum arrester. Containing jars are used to hold the greater quantity of electrolyte and give greater cooling surface. The characteristics of this arrester differ in some details from the cone type previously described. The direct-current arrester has no series gap. It is connected to the circuit directly and has a small leakage current flowing through it constantly. In consequence of having no series gap its dielectric-spark-lag is zero.

A brief review of the practical properties of the 600-volt direct-current arrester is given below:

There is no series gap. The normal leakage current is 0.001 ampere. The discharge rate at double voltage increases a million fold, it is 1000 amperes. Internal resistance above the *permanent critical voltage* is a fraction of an ohm. It may be frozen. Its inductive length of circuit is small. Its equivalent-needle-gap is 0.00 in. as compared to other types of arresters which give 0.25 in. to 0.58 in. under the same condition of test. Its measured static capacity is equal to over 400 miles of trolley wire.

Temporary and permanent critical voltages. A condition which may be designated as a temporary critical voltage of the film valves is prominent in this arrester. If an arrester is on a 600-volt circuit taking one milliampere of current and the voltage rises to a slightly greater value, say 625 volts, the current will suddenly rise to several amperes. If the voltage is maintained, a thicker film is formed which again reduces the current to a few thousandths. If the voltage decreases again, this extra thickness of film is re-dissolved. The *temporary critical voltage* of the film then is the constant running voltage. From another point of view, this statement is equivalent to saying that the arrester begins to discharge at a high rate of current the instant the voltage begins to rise. This is in contradistinction of all gap types of arresters which do not begin to discharge until the spark potential of the gap is reached. The *temporary* is to be distinguished from the *permanent critical voltage* of the film. If the voltage impressed on this arrester should rise to about 840 volts the limit of film formation is reached. Every volt pressure rise above this value causes an increase of current which is permanent so long as the voltage remains constant. This passage of current through the film should be carefully distinguished from the usual failure of a dielectric. For illustration, a thin layer of mica may have several thousand volts impressed upon it before it disrupts. This disruption will take place at one point and the voltage will drop to about 50 volts which is the ordinary arc voltage. The aluminum film does not function this way. The exact physical phenomenon is obscure, but it is evident that there is no analogous drop of potential at the film when the heavy current discharges and furthermore the current is distributed over the entire surface.

The nature of the film varies with the electrolyte. As a working hypothesis it is assumed that it consists of pure gases in a liquid form held in a hard insoluble skeleton of aluminum hydroxide. This is borne out by most of the observed phenomena and so far as known is not disproved by any.

EARTH CONNECTIONS

The ohmic value of the earth resistance in connection with protective apparatus is usually unknown. The usual directions for making an earth connection are one or more of the following.

a. Bury a slab of copper about two feet square in coke.

b. Connect a wire to the water mains.

c. Locate a copper plate in the mud of a body of water.

The first is expensive to install, is concentrated at one point, and has an unknown value of resistance which may vary greatly from a change in moisture. The second gives a low value of resistance as a rule but is not available on lines and in many sub-stations. The third may give a low resistance but usually has an objectionably long earth connection.

With the object of learning the effect of distance between earths on the ohmic resistance, effect of the size of the earth plate, depth of conducting stratum and the most economical method of reaching it and maintaining contact, the writer has made a series of tests, several of which are given below. Some of these tests were begun in 1906 and continued to the present.

Methods. The first consideration was the choice of a method of test. The method employing the Wheatstone bridge recommended in some publications on telegraphy is unsatisfactory on account of the counter electromotive force of contacts. The simplest test is the measurement of voltage and current at the convenient value of 110 volts impressed and the only question regarding this test was the choice between alternating and direct currents. Alternating currents gave the most satisfactory results. If one volt counter electromotive force was subtracted from the impressed direct voltage the same resistance was obtained as given by alternating currents, except in one case. In this case the iron pipe was driven vertically through a deposit of coal ashes and cinders. At 1 ft. depth the direct-current method gave a resistance of 36 ohms whereas the alternating-current gave a resistance of 26 ohms. Since this deposit of cinders and ashes was not thick, its relative effect disappeared at a greater length of pipe. At a depth of 8 ft. the values by alternating and direct current sensibly coincided. This difference in resistance seems to have been due to some effect analogous to that in a coherer. The 110 volts of alternating current were obtained by transformation from 2300 volts; the high-potential static came through the particular transformer so badly as to make the handling of a low-voltage wire exceedingly disagreeable. This high potential may have caused the particles to cohere. The direct current was taken from a battery.

In all tests 1-in. iron pipes were used. The lettered pipes were 5 ft. and the numbered pipes 8 ft. in the ground. The resistances were measured between each pipe and the water-pipe main and also between earth pipes. The resistance of the water-pipe main was 3.3 ohms. The resistance of the earth pipes varied from 10 ohms to over 1000, according to the condition of the earth.

Fig. 20 shows the location of the earth pipes; numbers 1, 2, 7, 9, 3, 8, and 5 are on the same level in wet or moist ground. No. 4 is in a pine grove on an upper terrace eight feet above in dry earth and No. 6 is on a terrace ten feet below in very wet earth. The distances between earths: from 2 to 7 is 5 in. (probably not accurate to 8 ft. depth), 7 to 9 is 1.6 ft., 9 to 3 is 4.75 ft., 2 to 3 is 6.5 ft., 2 to 8 is 33 ft., 2 to 9 is 1.9 ft., 3 to 7 is 6 ft., 2 to 5 or 6 is 650 ft. Pipe earths *B*, *C*, *D*, *E*, and *F* were given special treatment to increase the conductivity of the earth near them.

Resistance per foot depth of pipe. The curves, Fig. 21, show the resistance of each earth pipe at each increase of one foot depth. The water main is designated as *G*. *G*-1 means that the two are used as electrodes. The first measurement taken was with the

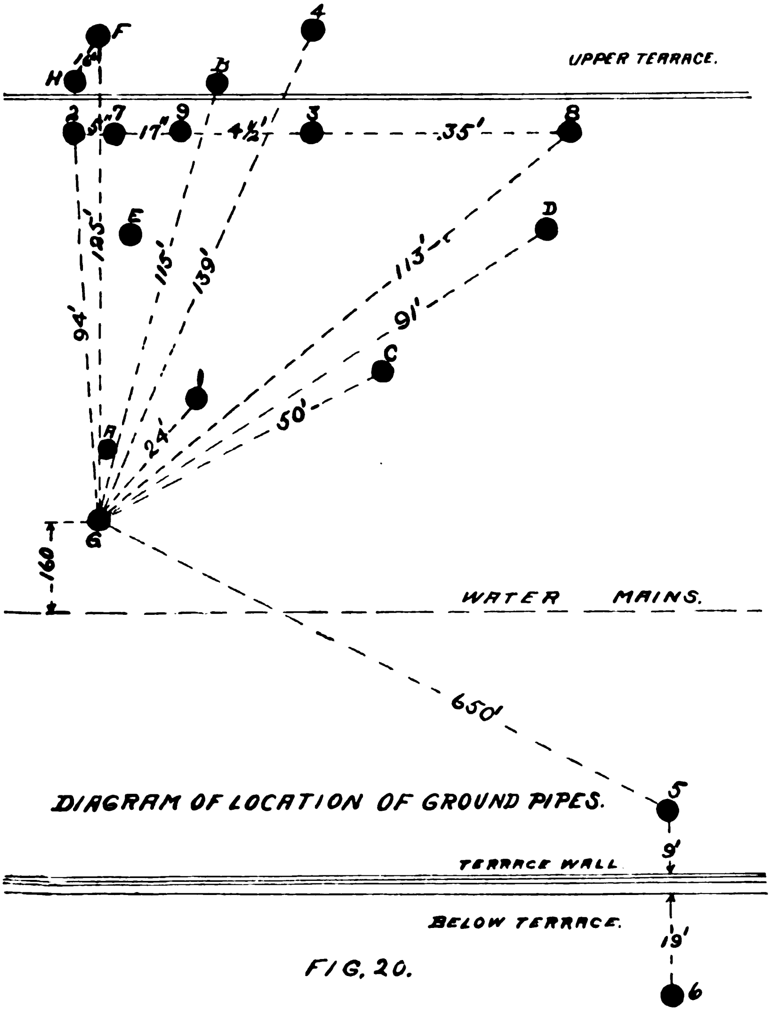


FIG. 20.—Map of earth pipes at the laboratory

pipe resting on the surface of the earth. The resistances of these various connections varied from 1000 to 8000 ohms and cannot be shown on the scale of the print. The curves show that pipe No. 1 was well into the conducting stratum at 1 ft.

depth; Nos. 2 and 3 at about 2 ft. depth; No. 6 below the wall at about 3 ft. and No. 4 on the dry upper terrace had to be driven about 7 ft. before it penetrated the conducting stratum. No. 5 at 8 ft. depth is equal in resistance to No. 1 at 1 ft. depth only.

Comments on the change of resistance per foot. From the curves of Figs. 21 and 22 one may conclude that in making a pipe ground there is little to be gained in conductivity in driving a pipe more than 3 to 6 ft. into the conducting stratum. Comparing the resistance between pipes 2 and 1 at different depths it will be seen that at the surface the resistance decreases in proportion to the depth but already at 2 ft. depth the area or depth is increased 100 per cent. over 1 ft. yet the resistance decreases only 46 per cent. The ratio of these percentages is roughly 2½. Between 7 and 8 ft. the area increases 14 per cent. but the resistance decreases only 3.4 per cent. The ratio of these percentages is roughly 4. In other terms the resistance is only decreasing one-fourth as much as the area is increasing. In fact this curve

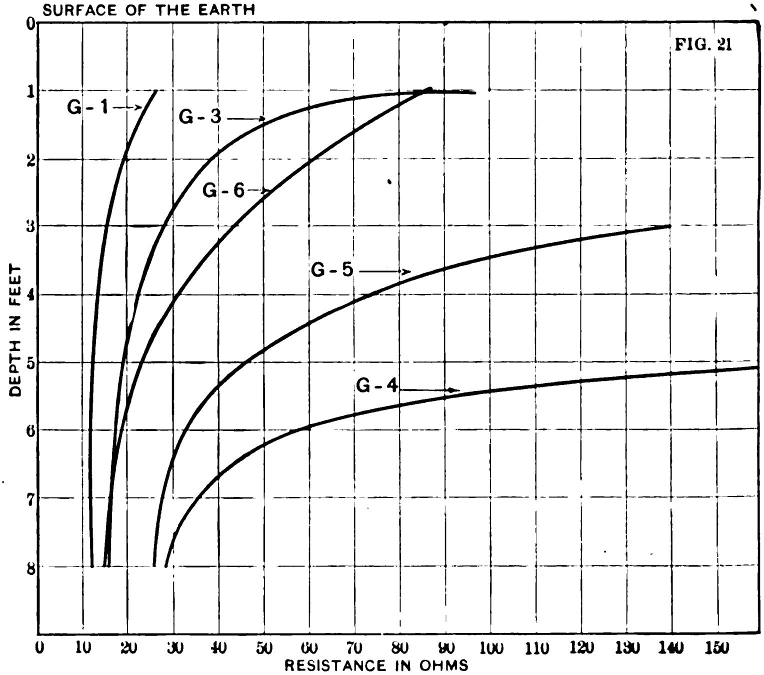


FIG. 21.—Resistance of an earth pipe at every foot increase in depth

is logarithmic and theoretically nearly reaches zero resistance when the pipe is infinitely long. Since the specific resistance of the earth varies with the depth the equation of the curve is not simple. There are two parts to it. The equation for the greater depth is $f = 100\ (k - b)^{A}$

Between pipes Nos. 2 and 1 the numerical values are:

$$f = \text{feet depth},\ k = \frac{1}{\text{resistance}},\ b = 0.0035 \text{ and } A = 2.$$

Fig. 22 shows the resistance of each pipe earth relative to and including No. 2.

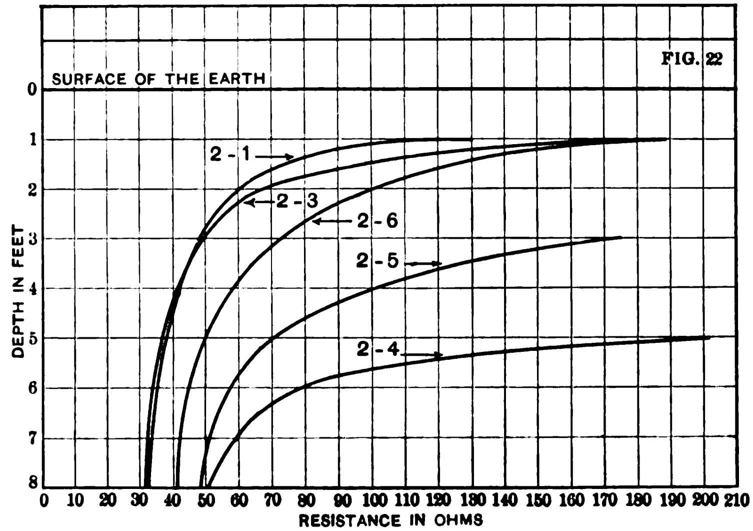


FIG. 22.—Resistance between pairs of pipes at every foot increase in depth

EFFECTS ON THE RESISTANCE OF VARYING THE DISTANCE BETWEEN EARTH PIPES

The desideratum is to determine what distance apart pipes must be placed to give practically the maximum possible resistance. It is a well known fact that after a certain distance between earths is reached any further increase in distance will not increase the resistance between them. Fig. 23 shows the resistance taken between pipes set at various distances. The resistance reaches a nearly constant value at about 6 ft. separation. Therefore if it is desired to place a ground resistance in series between phase and phase of a line as suggested by Dr. C. P. Steinmetz some years ago, it is necessary to separate the ground pipes only by this distance. In other words it is not necessary to make one at one pole and another at the next pole.

Treatment to improve earths. The material of the earth in this locality seems to be a mixture of clay and sand. Five pipes having a length of 5 ft. each were used in this test and are designated by the letters *B*, *C*, *D*, *E*, and *H*. The variable resistance of each of these earths relative to time, is shown in Fig. 24. Tests were made for eight consecutive days.

Earth *B* was made by digging a post hole and mixing the dry earth with 16 pounds of salt and pressing the mixture back into the hole around the pipe. Water was then poured around the top of the hole. This pipe was located on a projection of the terrace, 8 ft. high, so that there was a sudden drop on one side of 8 ft. and on the other side a drop of 4 ft., to a ditch. The resistance of the earth decreased daily showing that the salt water was percolating from the dry earth of the knoll down to a conducting stratum about 3 ft. below the pipe. During the eight days water was poured onto the top of this earth four times. It has now stood one year and seven months and the ohmic resistance has not varied materially.

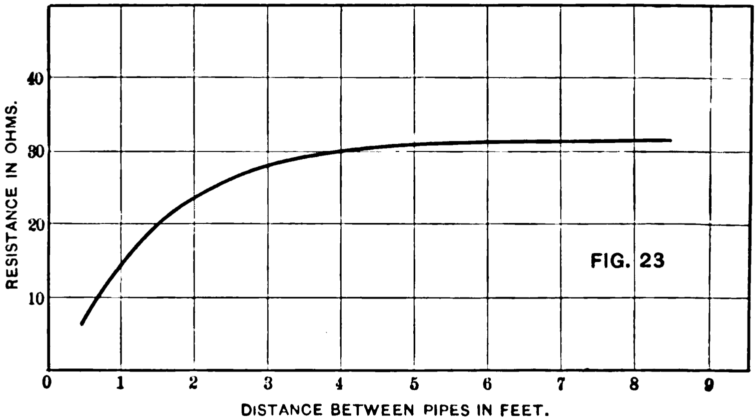


FIG. 23.—Resistance between pipes with the distance between them variable

Earth *C* was made by digging a post hole, pouring into this hole sixty pounds of lime, sixty gallons of water, and filling in with dirt around the pipe. The location of this earth was below the terrace in good ground. Earth *C* is located quite near the previous mentioned earths designated as 2, 7, 9, and 3, and this treatment added nothing to the conductivity of the already moist earth.

Earth *D* was formed by simply driving a pipe 5 ft. into the earth, cupping out around the pipe at the top. Four pounds of salt were then placed in this cup and water was added. Twice subsequently, water was added. Results are shown by the curve.

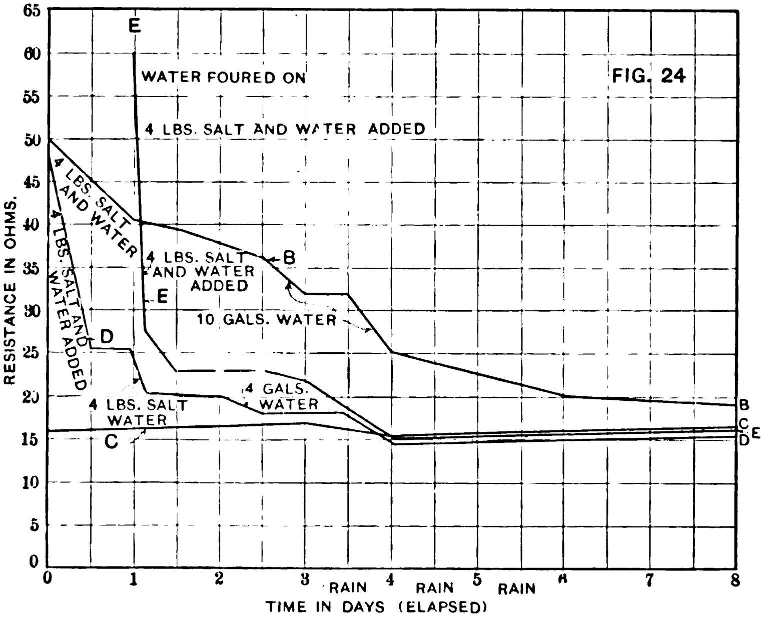


FIG. 24.—Decrease of resistance versus time after pipes have been treated with salt water

Earth *E* was formed by laying a pipe on the level ground and covering with earth. Salt was then scattered over the earth and water poured on the mound. In this case fairly good conductance was obtained 1 ft. below the surface. This fact is indicated in the curve sheet by the sudden drop in the resistance from 60 ohms to 26 ohms during the same day.

Earth *H* was formed by laying a pipe horizontally in a shallow ditch and covering with earth. Fourteen pounds of salt were mixed with the earth and then water poured over all. This earth was located on the edge of the upper terrace which is 8 ft.

high. The initial resistance before water was added was 545 ohms. After two and one-half gallons of water were added, the resistance dropped the same day to 87 ohms. Water was added each subsequent day and after six days the resistance had gradually dropped to 25 ohms, (these results are not shown in Fig. 24). They are most remarkable, however, in that the salt solution had to percolate about 8 ft. before it struck a stratum of good conductivity. After one year and seven months the rain has washed out some of the salt from the covering of dirt about one inch deep, and the resistance has risen, but it is still less than one-quarter its original value.

The conclusions drawn from these tests are that the conducting stratum of earth can be reached and maintained by the addition of salt and water around the pipe. It is reasonable to infer that if the soil is sandy a greater amount of salt would have to be added. The salt in itself is hygroscopic and will always retain a certain percentage of moisture. In localities where the rain washes the salt through to the conducting stratum rapidly, it will be advisable to add salt at least once a year.

FIG. 25.

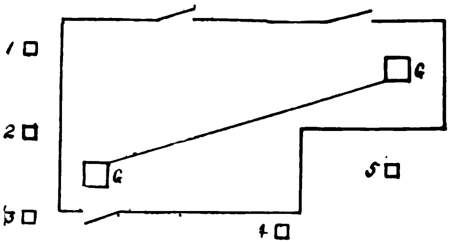


FIG. 25.—Map of earths at the sub-station of the Animas Power and Water Company

Multiple pipe earth connections. The same set of pipes (2, 9, 7, 3, and 8) used to obtain the variation of resistance with the distance between electrodes, was also used to get the variation in resistance, by putting the different ones in parallel. Numbers 2 and 7 were driven 5 in. apart. There is no material variation in the resistance of these two earths, whether multiple or singly—the value is about 16 ohms to the water main. If, however, No. 2 is combined with No. 3, which is 6,8 ft, away in a line parallel to the water main, the resistance of the two in multiple is only 10.7 ohms. The data are:

$G+(2)$ = 16 ohms.
$G+(7)$ = 15.9 "
$G+(2, 7)$ = 16 "
$G+(3)$ = 19.3 "
$G+(2, 3)$ = 10.7 "
$G+(8)$ = 21.6 "
$G+(2, 8)$ = 9.8 "
$2+(3)$ = 28.7 "
$2+(7)$ = 0.755 "

By algebraic combinations, the calculated resistance and conductance of each pipe is found.

Pipe No. 3 = 16 ohms = 0.0625 mhos
" No. 2 = 12.7 " = 0.0787 "
" No. 8 = 18.3 " = 0.0547 "
Water main No. 9 = 3.3 " = 0.3030 "

If these resistances are combined by the ordinary rule for parallel resistance, the values are different from the measured ones.

By formula Nos. 2 and 7 in parallel is 8 ohms, but measure 12.7.

By formula Nos. 2 and 3 in parallel is 7.07 ohms, but measure 7.4.

By formula Nos. 2 and 8 in parallel is 7.5 ohms but measure 6.5.

Incidentally, the last reading is in error due to leaving the current on too long. Later it will be shown that when a pipe earth rests after carrying dynamic current for a while, the conductance increases.

General law for pipe earths in parallel. In order materially to reduce the resistance of a pipe earth by additional electrodes, the added pipe must be driven out of the denser stream lines of current of the pipes already driven. As example, No. 7 was driven in the dense stream lines of No. 2 and did not lower the resistance by a measurable value whereas No. 3 was pretty well out of the stream lines and nearly follows the well known laws of paralleling resistances. Figs. 26, 27, 28, and 29, show the stream lines for various conditions; Fig. 26, vertical pipe and water main; Fig. 27, horizontal current lines between two vertical pipes; Fig. 28, roughly the vertical cross section of current stream lines between two pipes partially driven. The two logarithmic factors are represented, one by the straight lines and the other by the curved lines—Fig. 29, current stream lines of a pipe touching the surface. The similarity of these current lines to the static field around a charged conductor is evident, in fact if the earth is assumed to have uniform resistivity, the laws are almost identical. As an example of the relation, the capacity of a single conductor 0.18-in. diameter and 75 in. from the earth is 0.0169 microfarads and the capacity of a conductor twice the diameter is only 0.0195 microfarads; in other words, an increase in size of 100 per cent. increased the dielectric displacement current only 15 per cent. If the earth pipe is driven several feet to minimize the proportional effect of the tip and lines represented in Fig. 29, the same law should hold approximately true for dynamic current as for displacement current; consequently with one earth pipe resistance known, the resistance of

FIG 26

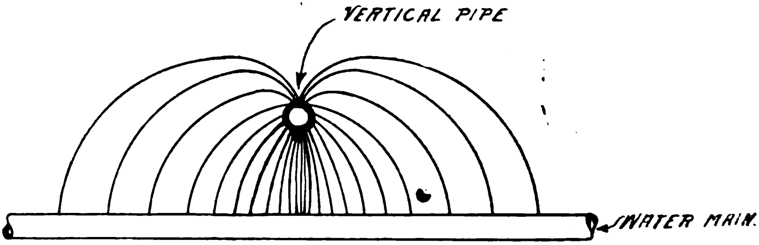


FIG. 26.—Current stream lines between a vertical earth pipe and a horizontal water main. They are similar in form to a static field

FIG. 27

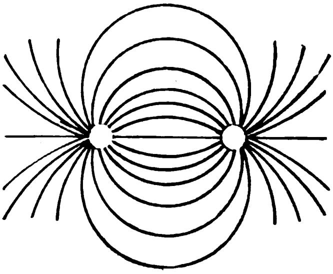


FIG. 27.—Current stream lines (horizontal section) between two vertical pipes

a pipe of different diameter may be estimated from appropriate tables of static capacity. Returning to the static analogy, if another line wire 0.18 in. diameter is strung parallel to the first at a distance of a few feet, the capacity of the two in parallel is twice 0.0169 microfarads. Analagously, the conductance of two earth pipes is increased.

Values of resistance of the condition of the pipe touching the surface (Fig. 29) are herewith given on account of their relation to a broken line wire touching the ground. Pipe No. 1 was 1200 ohms, No. 2 was 1260 ohms and No. 4 was 6000 ohms.

FIG. 28.

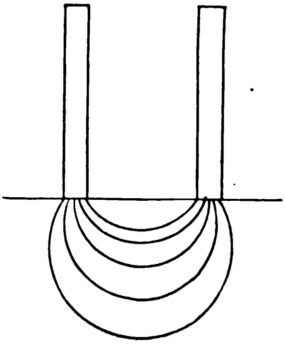


FIG. 28.—Current stream lines (vertical section) between two vertical pipes touching the surface of the ground

FIG 28a

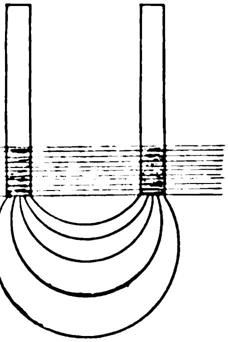


FIG. 28 a.—Current stream lines (vertical section) between two earth-pipes partially driven. The two sets of lines represent the two logarithmic factors of the equation of the resistance

In connection with the subject, the drying out of the earth by dynamic current as given later should be noted.

Animas earth tests. These tests of earths around the laboratory were supplemented by measurements of earths on the Animas Power and Water Company's system. Fig. 25 is a map showing the location of the earths at the sub-station near Silverton. The ground in this locality is principally the gravel washed down from the steep mountain sides. The Animas River flows past the sub-station at a distance of about 100 yards. Under the station floor at the two points shown are two of the old type grounds consisting of expensive copper plates buried in coke. These two together are designated as *G* in the notes. Around the building five iron rods were driven to a depth of 6 ft. entailing unusual trouble on account of the stones encountered. The tests are divided into six parts.

1. *Variation of resistance with depth (dry earth).*
2. *Variation of resistance with time after salting.*
3. *Measurements of resistance between pipes in variable multiple groups.*
4. *Measurements of resistance between the sub-station and Hobbs' Switch, 5.5 miles up Gladstone Canon.*
5. *Measurement of resistance between sub-station and power house 25 miles down the Animas River.*
6. *Measurements of resistance of tree earth, pole earth, railroad earth, and side hill earth.*

Variation of resistance with the depth as the iron rod was driven. All measurements made with the lighting voltage (125 volts approximately). Pipe No. 3.

Depth in feet	Resistance in ohms
1	604
2	172
3	250
4	312
5	125
6	161

The irregular variations are due to the lateral displacement of the iron rod as it pushed by some obstructing stone.

Time resistance variation after salting the rod at the surface of the ground.

Time in minutes	Resistance in ohms
0	161
5	62.5
10	47.7
30	38.5
360	33

This earth was located at the corner where all the rain water from the roof was carried. A storm occurred and considerable water was discharged around the pipe. Enough of the salt was washed through the gravel to raise the resistance from 33 to 35 ohms. The other earths were unaffected by the rains, *Measurements of resistance between pipes and various multiple groups.*

Earth pipes	Resistance in ohms	Pipes in multiple	Resistance in ohms
1 to 3	128	*G* to 1, 2, 3, 4, 5,	32.3
2 to 3	64	*G* to 1, 2, 4, 5,	36.6
4 to 3	128	*G* to 1, 2, 3, 4,	35.
4 to 3	115	*G* to 1, 2, 3,	37.1
3 to 5	107	*G* to 1, 2,	47.4
G to 5	85	*G* to 1, 5,	58.2
G to 1	115	*G* to 1, 3, 5,	39.4
G to 2	55.5	*G* to 2, 3,	39.4
G to 3	57.		

The individual resistances can be found by elimination in the algebraic equations, but the resistance of any earth pipe is not a constant; it depends on its relation to the other electrode. This is treated later. The values calculated are:

G = 22 ohms = 0.0455 mhos.
1 = 93 " = 0.0107 "
2 = 31.25 " = 0.0320 "
3 = 35 " = 0.0286 "
4 = 93 " = 0.0107 "
5 = 67.5 " = 0.0148 "

By summation of the reciprocals the calculated values of resistances of the pipes in various combinations are:

1, 2, 3, 4, 5, = 10.3 ohms = 0.0968 mhos, G by subtraction from tests = 22
1, 2, 4, 5, = 14.7 " = 0.0682 " " " " " " = 22
1, 2, 3, 4, = 12.2 " = 0.0820 " " " " " " = 22.8
1, 2, 3, = 14. " = 0.0713 " " " " " " = 23.
1, 2, = 23.5 " = 0.0427 " " " " " " = 23.9
1, 5, = 39.2 " = 0.0255 " " " " " " = 19.

1, 3, 5, = 18.5 " = 0.0541 " " " " " " = 21.

2, 3, = 16.5 " = 0.0606 " " " " " " = 22.9

Two salient features of these tests are: first, the low total resistance of the five pipes in parallel (10.3 ohms) as compared with the two station earths (22 ohms); second, the low cost and the easy and certain maintenance of the pipe earths as compared to the old type earths. The pipe earths are to be preferred, from every point of view.

Measurements of resistance between the substation and Hobbs' switch, 5.5 *miles up Gladstone Canon.* Three earths were made at Hobbs' switch and by means of the telephone wire connections were made between these earths and the earth (G) at the sub-station. No suitable measuring instrument was at hand so a voltmeter was used. The results are less accurate than the previous tests. In calculating the individual earth resistance the assumption was made that each earth carried a local value of resistance and that the rest of the resistance was in the main body of the earth between, or since there are mountains of granite in direct line between the two stations, that there was a resistance of the surface of the earth down one cañon to the fork and up the other, quite distinct from the local resistance. The calculated results seem to justify the assumption in this particular case. The Hobbs' earths were not salted and were made in ground through which snow water was percolating, consequently their resistances are high. The following values were obtained: Hobbs No. 1-437 ohms; Hobbs No. 2-100 ohms; Hobbs No. 3 (ground for telephone) 189 ohms; and the resistance of the telephone wire plus the 5.5 miles of earth between stations was 89 ohms. Subtracting the telephone wire resistance leaves the 5.5 miles of earth 36 ohms. The resistance to a lightning discharge passing along the wires cannot be less than this and is probably much greater.

Measurement of earth resistance between the sub-station and the power house, 25 miles down the Animas River. The total resistance, including both station grounds, the earth between and the line wire, was 55 ohms. The resistance of the power house earth plus the main body of earth was only about 30 ohms which is less than the main body of the earth to Hobbs' switch.

Measurement of the resistance of tree earth, side hill pipe earth, pole earth and railroad earth. Up on the gravelly hill side about 100 ft. above the substation was an evergeen tree. A line of nails was driven into the tree just above the ground and wired together. Six feet higher another set of nails was driven. The tree at the base is 5 ft. in circumference and at 6 ft. up is 4 ft. in circumference. Resistance of the base of the tree to station earth is 770 ohms and from the point 6 ft. up is 2820. Resistance per foot height of tree 340 ohms. An iron pipe driven 5 ft. near the tree measured 353 ohms dry and 190 ohms a short time after it had been salted down and wet with a bucket of water.

Seven nails four inches long were driven around the circumference of a spruce transmission pole just above the ground.

The pole stood on a level with the sub-station. The resistance to the sub-station earth was 1290 ohms; 14 in. higher up it was 3300 ohms. Seven more nails were driven at the same height

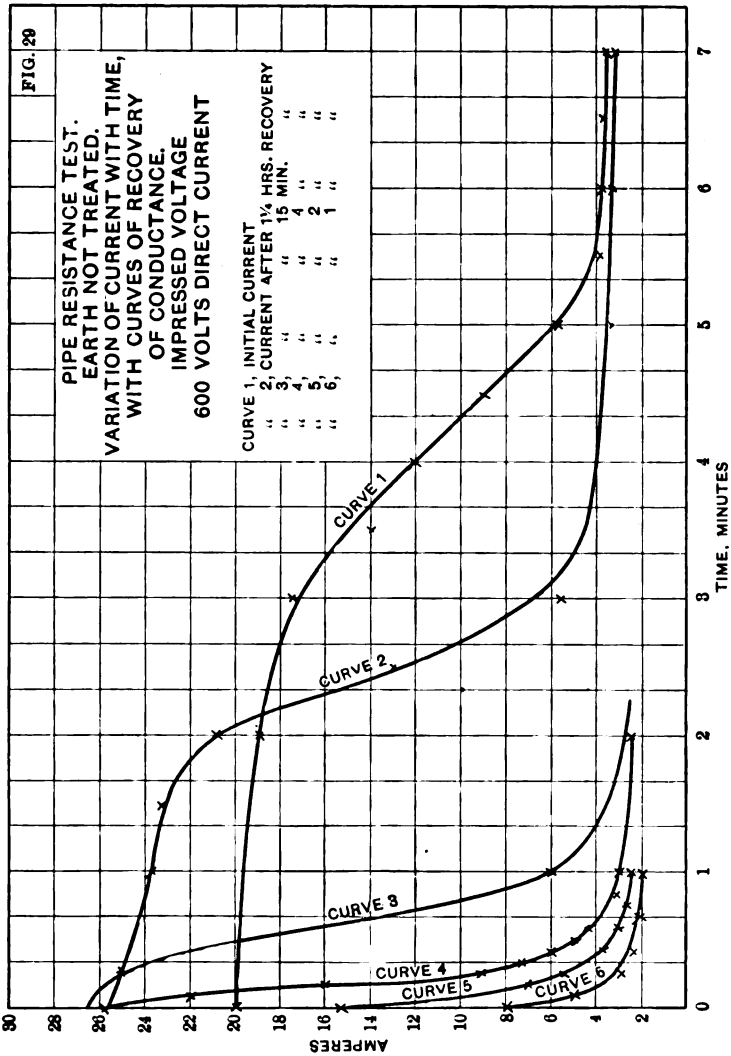


Fig. 29.—Curves showing the energy capacity of earth pipes, also curves of recovery of conductance
Earth not treated

to increase the area of contact. The resistance from the ground surface dropped to 980 ohms and correspondingly at 14 in. up it dropped to 2700 ohms. This gives about 1450 ohms per foot. At 6 ft. up, however, the pole was so dry that its resistance was too high to measure with a voltmeter having a scale of 150 volts and an internal resistance of 5200 ohms. The low resistance at 14 in. up shows the effect of capillary attraction in drawing up the moisture from the ground.

A resistance measurement was taken between the steam railroad track which parallels the main transmission line 35 miles and the sub-station earth No. 3. The total value was only 46.5 ohms which leaves 11.5 ohms for the railroad.

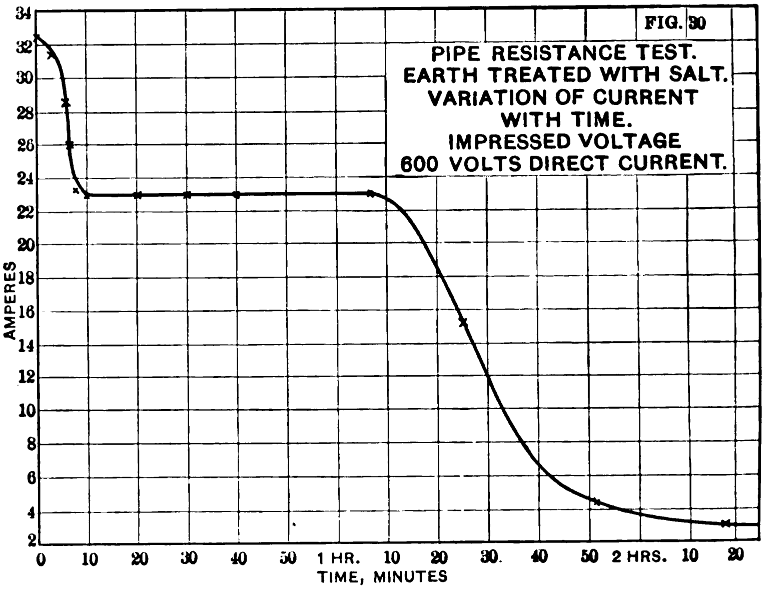


Fig. 30.—Curve showing the energy capacity of the same earth pipe salted

Earths Carrying Dynamic Current

Variation of earth contact resistance when dynamic energy is applied. Occasionally dynamic energy is passed through the earth connection. This may occur: first, when arresters connected to different earths operate simultaneously; secondly, when a phase of a grounded neutral system is accidentally grounded; thirdly, to a less degree, when a phase of a non-grounded neutral system is accidentally grounded; and fourthly, when single-phase arresters are used connected to different earths.

A study of the effect of dynamic energy was made on pipe earth No. 1 near the laboratory, under the two conditions of unsalted and salted. The pipe was 1.25 in. outside diameter (known as inch pipe) driven to a depth of 8 ft. 600 volts direct current potential were impressed. The results are shown in the three curve sheets Figs. 29, 30, and 31. Fig. 29 gives curve of the unsalted earth and Figs. 30 and 31 of the salted earth.

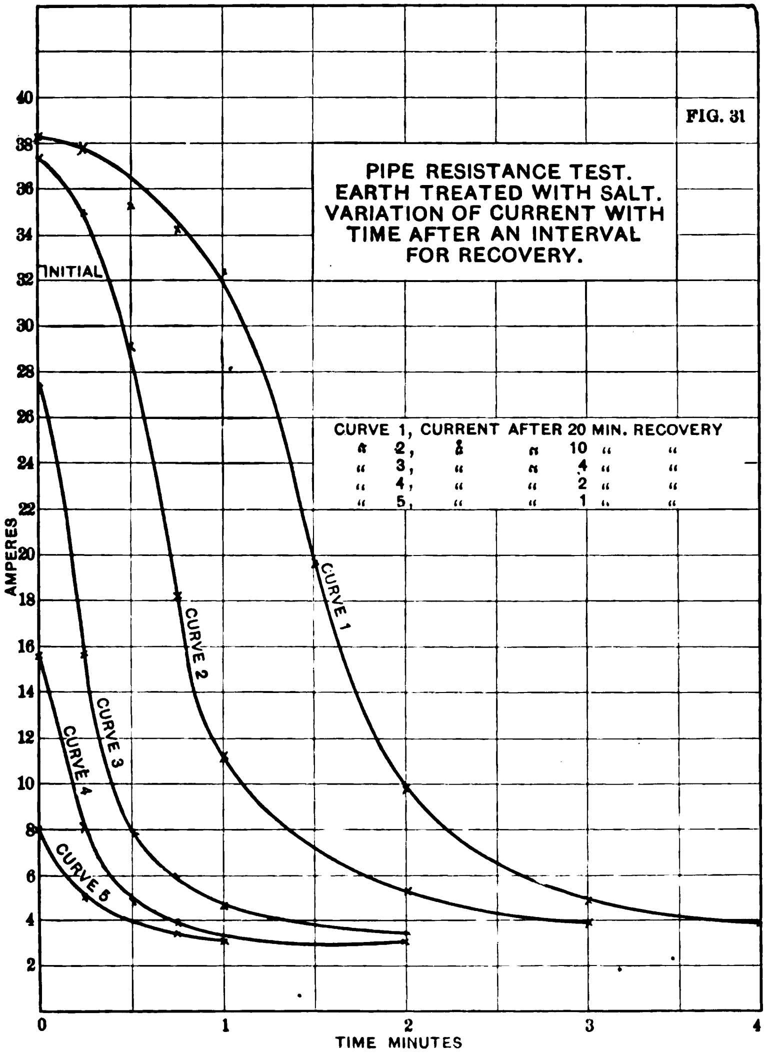


Fig. 31.—Curves of recovery of conductance of the same salted earth-pipe

The characteristic behavior was the same. At first there was a fairly steady current flow until the temperature increased sufficiently to make the pipe steam and boil away the moisture, then secondly, a rapid drop of current to a fairly constant value such that the moisture was supplied from the surrounding earth as rapidly as it was evaporated. This supply of moisture could go on indefinitely only if the pipe were driven into a sink or a subterranean stream. Thirdly, when the potential is removed there is a rapid recovery of conductance. Fourthly, there is finally, after a few minutes repose, a higher conductance than existed initially.

Between the unsalted and the salted earth there is a marked difference in the endurance or kilowatt capacity. The unsalted earth carried 20 amperes for 3 min. (12 kw. for 3 min.) before it began to lose its conductance, whereas the salted earth carried 23 amperes for 70 min. (13.8 kw. for 70 min.) which is 20 times as much. The unsalted test was made one day and the pipe was then salted down and left until the following day, about 18 hr. While the salted earth was being tested chlorine gas was given off.

FIG. 32.

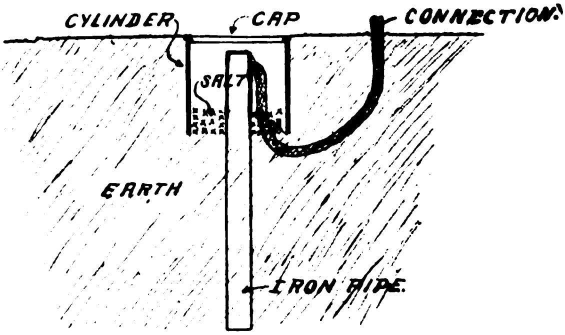


FIG. 32.—A recommended form of pipe earth unit

Form of pipe earth recommended. Any kind of metal pipe or rod driven into the earth a few feet makes a good earth connection if the soil around the pipe at the surface is cupped out, filled with a few pounds of salt, and water added. A neater form of earth unit is shown in Fig. 32. A cylinder of metal or earthenware of any available diameter is set around the pipe at the surface of the ground and covered by a lid. This receptacle will hold the salt. Its advantages lie in the easy inspection of the connection and protection of surrounding vegetation from the saline water.

Last year it was proposed to draw some distinction between the general use of the words "ground" and "earths" as a matter of convenience and clearness; for example, a lightning-arrester may be grounded to a cable sheath or a transformer case and still be not earthed at all, unless these parts should be earthed; on the other hand, the arrester may be grounded to a pipe earth or to a system of pipe earths. This distinction will be somewhat justified in the grounding methods described in the following.

It has always been customary to speak of a low-resistance earth as advisable and necessary to the proper functioning of a lightning-arrester. Obviously, this is not always true. It is true as a protection to insulators but not so as a protection to isolated apparatus. While it is not the object of this paper to encourage the use of high-resistance earth, a method of grounding will be shown that does not diminish the protection in spite of a high-resistance earth connection. There are three factors involved which require separate treatment; namely, (*a*), the resistance factor; (*b*), the inductance factor; and (*c*), the permanence.

Station grounds. a. The resistance factor. The object of protective apparatus is not to prevent a rise in potential but to prevent an increase in difference of potential between the line and metal bodies or cases. To accomplish this the lightning-arrester must limit the potential between its terminals; at its lower terminal it should be connected to the metal cases of the apparatus and to a system of pipe earths encircling the station. If the resistance of the pipe earths is so high as to limit the discharge, there will be a drop of potential from the outside of the station to the point under the line whence the charge came. The potential of the station may actually rise momentarily thousands of volts above the surrounding country, but this is of no consequence because the potential of everything in the station rises simultaneously.

There is one source of danger which should be avoided. If a water main runs into the station it should be connected to the multiple pipe earth, because if its resistance is low compared with that of the pipe earth a person could get a shock from a charge passing from the station into the water main. If it were not for the danger of the water main, a fairly high resistance of multiple pipe-earths would be advantageous in using up the energy of the lightning stroke without risk of the $I R$ drop causing a dangerous difference of potential. In isolated stations where there is nothing corresponding to a water main, multiple pipe earths around the building connected to the transformer cases should be sufficient. That is to say, a long lead running to the mud of an adjacent stream is needless.

The bearing earth connection resistance has on the protection of insulators, so far as known, may be theoretically explained. The only protection there is for an insulator is a lightning-arrester placed in the region of induced static from the clouds. The station arrester acts as a protection to insulators only when the inducing cloud is over the station. If the resistance of the multiple pipe earth is high it will, in the latter case, give theoretically a somewhat less protection to the neighboring insulators. Since salted multiple pipe earths, even under the very worst conditions, give lower resistance than the old method earth, there is no choice between them.

b. The inductance factor of earth connections. Since the resistance factor is brought to a matter of indifference by the multiple pipe earths, the inductance factor should be considered. It was feared that the iron pipe would offer greater inductance to high frequency currents than copper wire. Dr. C. P. Steinmetz has made calculations which show that the pipe is actually a better conductor of high frequencies than a large copper wire. Regarding the connections between a lightning-arrester and earth the rule has always been to make it as short as possible. It is advisable to drive a pipe earth directly underneath the arrester even if such earth must be of relatively high resistance. This earth should be connected to the other earths. A more general rule is: make the circuit between the line and earth through the arrester short relative to the length around through the apparatus to the earth. A choke-coil gives considerable added length. While this precaution may not be followed rigidly in high-tension apparatus, it seems to be extremely important in low-tension apparatus, especially with railway motors. Double-cotton-covered wire is delicate insulation. Some concrete ideas of what is possible if a storm cloud is over a trolley line may be gleaned from laboratory tests. With two leyden jars of the gallon size, giving a frequency of about two million cycles per second and a momentary current rush estimated at

1000 amperes, the potential drop along one foot of No. 10 B. S. wire will puncture the insulation between two wires, each double-cotton-covered; that is, four layers of cotton covering. The shortening down of the lightning-arrester circuit to the last possible inch may seem over cautious. With the old types of lightning-arresters which contain an appreciable internal resistance it is needless precaution, but the new aluminum arrester for railway circuits has an equivalent-needle-gap of 0.00 inches, an inductive circuit of only a few inches, internal resistance of only a fraction of an ohm, no series gap and a discharge rate of over 1000 amperes at double line voltage. Its normal leakage current is only about one millionth of this or 0.001 ampere.

While this arrester is designed to take care of the severest induced strokes it cannot of course prevent a drop of potential along its connecting lead. The ideal connection of this arrester to a trolley car consists in a lead carried from the trolley down near the motor or truck frame, connected to the lightning-arrester, and then carried back, not in the same conduit, to the car wiring. Nearly all the types of car wiring give this condition with varying degrees of perfection. While in most localities the lightning troubles encountered may not warrant the expense of rewiring, it is important to examine these features when the aluminum arrester is used in localities where the lightning is especially severe and frequent.

So far, only the length of lead has been considered. It is sometimes impossible to shorten a lead below a given length and still important to reduce the impedance of it. Since the smallest wire that will carry the dynamic discharge of an arrester has a negligible ohmic resistance, the shape of the conductor only need be considered. Theoretically, the inductance decreases nearly in proportion to the increase in metallic surface.* The equivalent-needle-gap, however, shows a less gain as the surface increases. The following measurements give relative concrete values of potential drop under nearly the same condition as that noted just above. A 5 ft. length of copper ribbon 2.5 in. wide and thin as paper was connected in series with an equal length of No. 10 B. & S. wire. The equivalent-needle-gap of the strip was $\frac{3}{16}$ in. (0.476 cm.) and of the wire $\frac{7}{16}$ in. (1.11 cm.). The potentials corresponding to these values of needle-gap are 3760 volts and 8750 volts effective—about two and one-fourth times as great. Using peak values, the potential drop per foot along the wire was 2470 volts.

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* C. P. Steinmetz and K. Ogura, "Inductance of Straight Conductors".

From the known data a value of current may be obtained by substituting in the equation $E = L\omega I$. The frequency was two and one-quarter million cycles per second, consequently the current must have been greater than 550 amperes. A partial check on this value may be made by assuming zero resistance and calculating the current by the previously given equation involving the total circuit.

$$I = V\sqrt{\frac{C}{L}}$$

By this equation the maximum possible momentary value of current in this circuit is 3000 amperes at 100,000 volts impressed potential.

The foregoing calculations indicate that a discharge of current and frequency so high will tax both the resistance and the inductance limitations of an arrester to the utmost. The practical question yet to be answered is when and how often may these conditions arise? A speculation is useful to the observer and student of this phenomenon.

First of all the conditions may be obtained when a direct stroke hits the line; but such a discharge does not, in general, reach the lightning-arrester. It is probable that it may happen to a degree when a car or station is underneath a thunder cloud which discharges to the earth. It seems quite certain that it cannot happen from a traveling wave along the line because of the relative valve of the inductance of the line to the capacity. It seems safe to presume that the combination of high frequency and large current occurs infrequently at an arrester.

The permanence factor of earths. The permanence of the conductance depends on the moisture. Tests have been made using 600 volts on a pipe earth to drive out the moisture. In this case there was no baking of the material surrounding the pipe and consequently there was a quick recovery of conductance. No tests with more power and higher voltage have been made and possibly a more lasting effect might be produced by a grounded phase on a grounded neutral system. If such occurred during a storm the multiple pipe earths would be especially valuable.

Lightning conductors for the protection of buildings. The customary lightning conductor is usually connected to a single earth by a single conductor. Numerous cases of side flashes from the rod into some part of the building have been recorded. The following recommendations based on minimum inductance and screening are made:

Assuming a pointed roof for simplicity of illustration, a rod should be carried up high enough to act as an electrode for the lightning arc probably six feet or more, basing the distance on photographs of the part of the rod rendered luminous by the lightning. From a point about midway up on this rod, at least eight copper or iron wires should be attached; a wire passes to each corner of the roof and one at each mid-point. Each wire is carried directly down to a salted pipe-earth. At the eaves a horizontal metallic connection should be made to equalize the potentials and again at the ground line. The natural inclination of high frequency currents to spread over a surface will tend to prevent a side stroke toward the interior of the building. The multiple earth will tend to equalize the potential over the entire building. With a given amount of copper, the more it is subdivided into multiple paths, the surer the protection.

The foregoing is intended to cover only the principle involved and will have to be altered somewhat to meet architectural demands.

CEMENT AS A RESISTOR.

Some time ago the possibilities of trouble with lightning-arresters on a system using cement resistors between the neutral of the system and ground suggested the necessity of studying its characteristics. It may be noted in passing, that arresters for non-grounded neutral systems require an extra leg between the multiplex connection and earth to limit the dynamic potential across the arrester in case of an accidentally grounded phase. If the resistance in the neutral rises appreciably, the condition is equivalent to a non-grounded neutral system.

Another important phase of the subject is related to the use of cement in poles and as anchors or foundations for electrical transmission towers. In the event of a shattered insulator, the cement or concrete will be called upon to carry either the charging current or one phase according to the connections. In this case the question of conductivity is a minor matter and attention should be directed to the possibility of disintegrating the cement by overheating. A series of tests was carried out to determine the characteristics to apply to the foregoing problems. The writer is indebted to Mr. R. H. Marvin for the tests. The report is so replete with data and conclusions it is given verbatim.

These tests were undertaken to determine the suitability of portland cement as a material for resistances, especially its use with large currents and on high voltages.

They tend to show the following conclusions.

At moderate temperatures the resistance depends simply on the amount of moisture in the cement and becomes extremely high if the moisture is removed, either by long drying or artificial heating. The addition of sand increases the resistance, acting apparently as an insulator distributed through it. When cement is heated it at first increases enormously in resistance as the moisture is driven off, but at a red heat it again becomes as good a conductor as when cool and damp. With the same voltage per unit of length, a moderate voltage, as 600 volts, will not heat the material above 100° cent. so as to pass the interval of high resistance; but a higher voltage, as 8000 volts, can pass this interval and heat the resistance to incandescence.

The subject will be treated under the following heads:

1. Effect on resistance of cement of various proportions of sand.
2. Change in resistance with age.
3. Behavior of cement resistances on constant potential circuits.
4. Effect of moisture on resistance.
5. Conductivity at high temperatures, or pyro-conductivity.
6. Change, from conductivity due to moisture, to pyro-conductivity with high voltages.
7. The properties of cement as a resistance when used in the form of concrete.

Subjects 1 and 2 are naturally included in the same tests and will be treated together.

1 and 2. *Effect on resistance of cement of various proportions of sand, and change of resistance with age.* Resistances were made up in the form of rods of square section. These rods were 14 in. long and had a cross-section approximately 2 in. by 2 in. or 4 sq. in. At 1 in. from each end, sheet iron terminals were inserted while the cement was soft. These terminals consisted of a strip of 17 mil. soft sheet iron, 2 in. wide and 2.5 in. long with a projecting lug for attaching a wire. The strip was slit for 2 in. into eight strips 0.25 in. wide; each 0.25 in. strip was then twisted through a right angle, giving a fork like appearance. This terminal gave a large area of contact without mechanically weakening the block. The terminals were thus 0.25 in. long in the direction of the axis of the rod, but in obtaining the specific resistance their distance apart, center to center, or 12 in. was taken.

The materials used were:

Edison portland cement and ordinary building sand.

Five different mixtures were tried, six rods being made of each. The materials for each set of six rods were mixed together so as to insure uniformity. The proportions were as follows, in parts by weight.

Set *A*.	Cement 1		Water 0.3
Set *B*.	Cement 1.	Sand 1.	Water 0.45
Set *C*.	Cement 1.	Sand 2.	Water 0.74

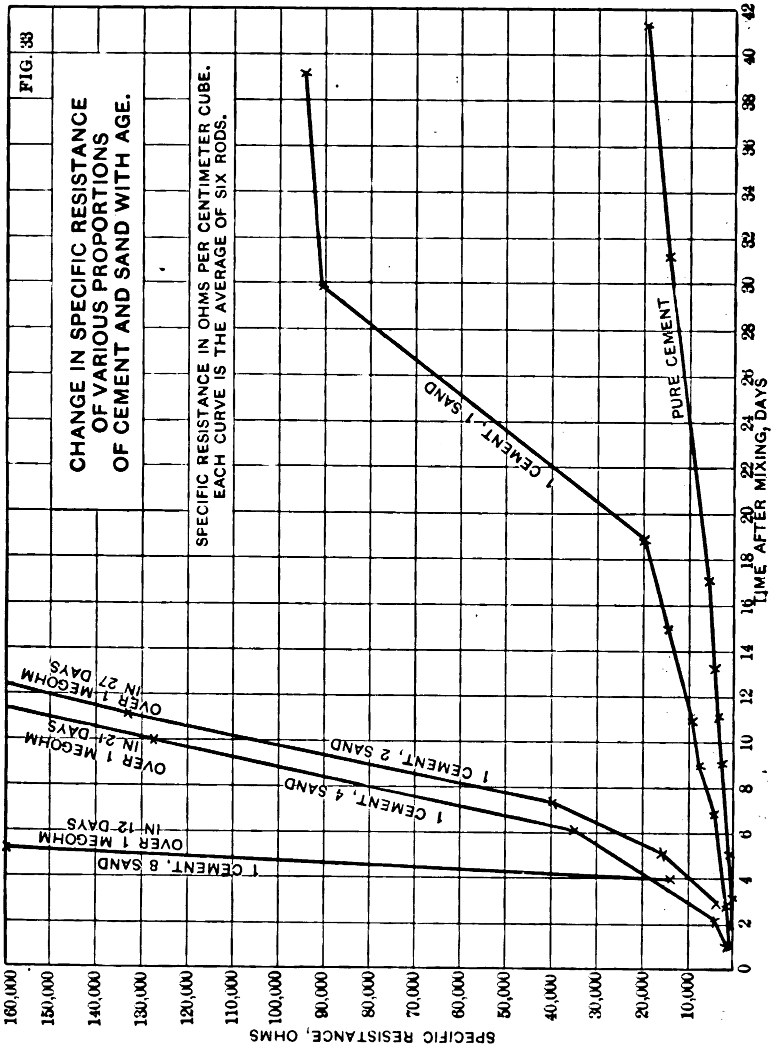

FIG. 33.—Time versus resistance of cement and sand

Set *D*.	Cement 1.	Sand 4.	Water 0.58
Set *E*.	Cement 1.	Sand 8.	Water 1.57

The rods of set *E* having such a large proportion of sand were very fragile for sometime after mixing, and never became very strong.

The resistance was measured on a storage battery circuit of about 110 volts by means of a voltmeter of known resistance. Resistances above a megohm could not be accurately measured, so when they occur they are

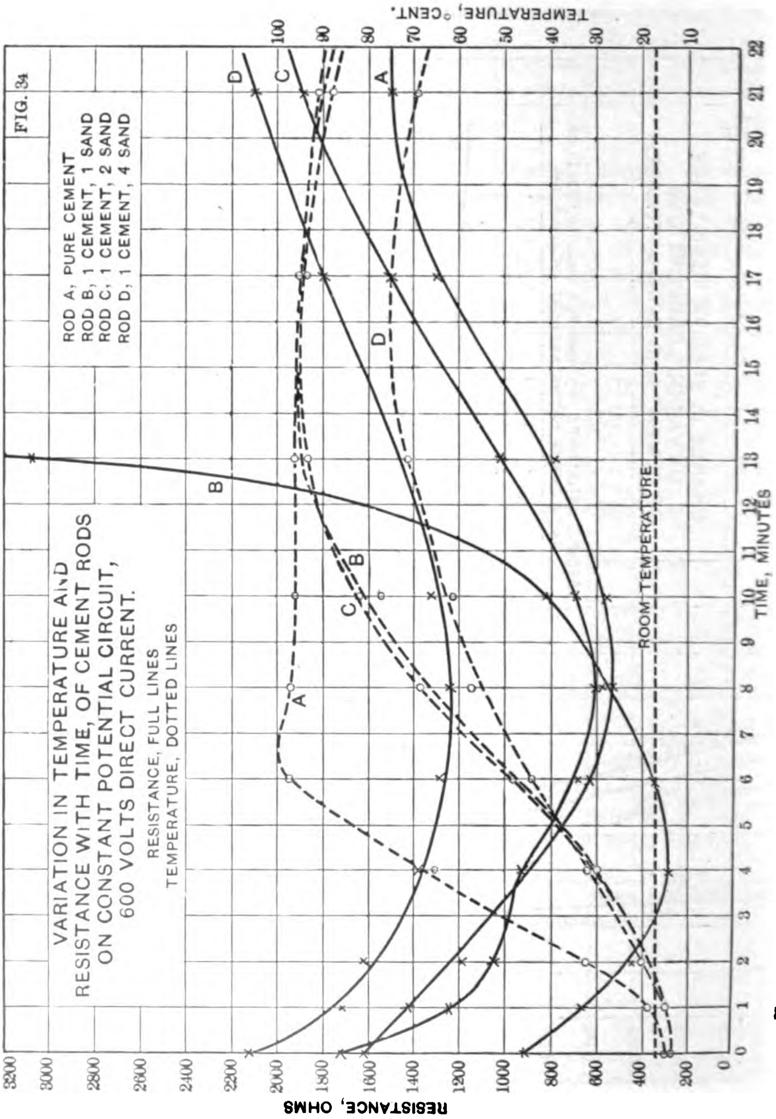

FIG. 34.—Application of power to cement resistors. These curves are of the early stages

simply indicated. Resistances were measured at intervals of a few days, the rods being kept in a moderately dry room.

The results are shown in Fig. 33, the resistance for ease in comparison being expressed as specific resistance, or resistance in ohms between opposite faces of a centimeter cube. These curves show a gradual increase in resistance with age; due apparently, mainly to drying out of moisture, but possibly in part to the chemical changes in setting. They also show a large increase in resistance with the addition of sand.

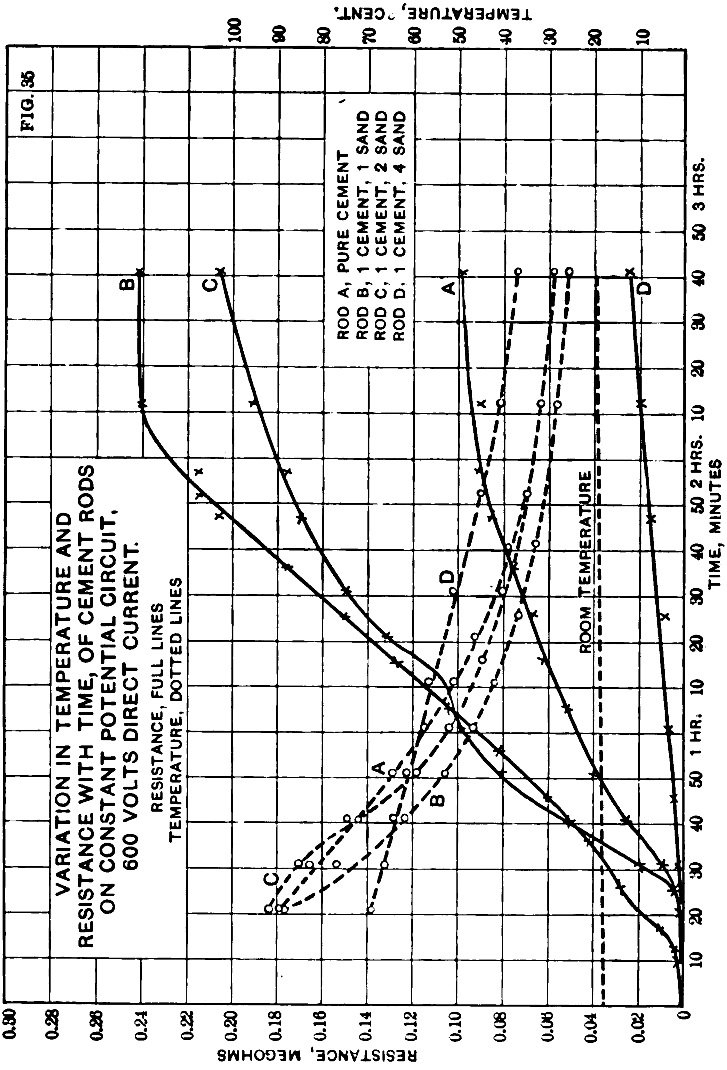

FIG. 35.—Application of power to cement resistors. These curves are the continuation of the previous curves to a smaller scale

3. *Behavior of cement resistances on constant potential circuits.* The tests on variation of resistance with age being concluded and all the rods being dry and well set, tests were next made to observe their action on a constant potential circuit. One rod from each of sets *A*, *B*, *C*, *D*, was

taken and soaked in water for sometime so as to insure uniform moisture conditions. After draining a few hours they were connected to a 600 volt direct-current circuit and readings taken of temperature and resistance at short intervals. The readings are plotted in the curves of Figs. 34 and 35. Fig. 35 is the continuance of Fig. 34 to a smaller scale of time and resistance. The resistances are those actually measured. The multipliers to reduce these to specific resistance are:

A	multiply by	0.836
B	" "	0.898
C	" "	0.907
D	" "	0.912

These curves show that the resistance at first falls rapidly, at the same time the temperature rising to nearly the boiling point. At this period a large amount of steam is given off. The resistance after reaching a minimum commences to rise. The temperature has a maximum occurring a few minutes after the minimum of resistance. After this the temperature continues to fall and the resistance to rise, both tending towards constant values.

It is interesting to note that rod *D* has the highest initial resistance and the lowest final resistance. The low maximum temperature attained, 75° cent. is the explanation of this, the initial resistance being so great that the rod could not heat up sufficiently to drive off its moisture in the time taken for the test. The initial resistance of *B* being lower than *A* is rather peculiar, in view of the curves obtained on drying out the rods, but is probably due to *B* having soaked up the water more thoroughly than *A*.

The amount of energy dissipated before the resistance has increased to a prohibitive extent is also of interest. If we consider three times the initial resistance as the permissible amount, then these rods gave the following results approximately.

	Time in minutes to reach three times initial resistance on 600-volt circuit	Kilowatt-hours absorbed and dissipated	Average kilowatts input
Rod *A*.........	28	0.0885	0.190
Rod *B*.........	13	0.0713	0.329
Rod *C*.........	26	0.0845	0.195
Rod *D*.........	56	0.1170	0.125

4. *Effect of moisture on resistance.* The tests already described indicate the importance of the moisture in the rods, but to further prove this point the following test was made. Two rods of each set, *A* to *E*, were taken. They were soaked in water for several days. When removed they were allowed to drain a few hours, and the resistance was then measured. They were next slowly heated over a bunsen burner for several

hours so as to drive out the moisture. After cooling the resistance was measured. They were again soaked in water as before and the resistance measured. The specific resistance in each case is given in the following table. Resistances over one megohm could not be accurately measured, so are simply indicated.

Specific Resistance

	A	*A*	*B*	*B*	*C*	*C*	*D*	*D*	*E*	*E*
	No. 1	No. 2	No. 1	No. 2	No. 1	No. 2	No. 1	No. 2	No. 1	No. 2
Wet before heating......	1078	1200	1552	1137	1930	1764	2240	1800	2910	3270
Dry after heating......	1 meg plus	1 meg plus	1 meg plus	1 meg plus	1 meg plus	1 meg plus	1 meg plus	1 meg plus	1 meg plus	1 meg plus
Wet after heating......	955	1270	1310	1483	2550	2810	2855	3490	6520	6420

This experiment agrees then with the others in showing that the conductivity is due to moisture.

5. *Conductivity at high temperature or pyro-conductivity.* Having shown that the resistance of cement increased enormously on heating sufficiently to drive out the moisture, the next point taken up was whether the resistance would again become lower on continuing to raise the temperature. For this a number of rods were made of pure Portland cement, 15/16 in. diameter and about 6 in. long. One of these rods was taken and provided with copper terminals placed 1 in. apart, each terminal being a sheet of strip copper ¾ in. wide, tightly clamped around the rod. Connections were made to a 116-volt storage battery so that the resistance could be determined by measuring the current in the rod and the voltage across it. The current was measured by a d'Arsonval galvanometer with adjustable shunt, and the voltage on a Weston voltmeter. Arrangements were made to heat the short length of rod between the terminals with a blast lamp. It was considered best to use as high a voltage as possible for measurement so as to render thermo electric effects negligible, preliminary tests having shown that these were very noticeable with low voltages. The following table gives a summary of the tests. The cement rods had been allowed two days to dry and set.

Variation of resistance of cement rod on heating.

Resistance megohms	Approximate temperature
0.144	Cold before heating.
54.500	
45.900	Slowly heating up
76.700	
8.970	Beginning to get red hot.
0.780	Red hot.
0.178	Partly white hot.
0.131	White hot.

These results are rather rough owing to the impossibility of heating the rod uniformly, and the absence of any means of obtaining the exact temperature, but they indicate the general principle that as the moisture is driven out the resistance increases enormously, but as red heat is approached, it falls rapidly, and at white heat is practically the same as when cold and moist. That this fall in resistance is due to temperature and not to a permanent chemical change is shown by the resistance returning to its high value when the rod cools.

The cement was rendered very weak and brittle by the heating, resembling a piece of chalk.

6. *Change from moisture conductivity to pyro-conductivity with high voltages.* The experiments of the previous section have shown that the conducting properties of cement depend upon three distinct states of the material. These are:

1. A condition of good conductivity depending in value upon the amount of moisture present. It is on this account liable to wide variation with time, and completely disappears when the temperature is raised to the boiling point of water.

2. A state of low conductivity, approaching that of a good insulator, when the cement is dry and its temperature below a red heat.

3. Another condition of good conductivity at and above a red heat; the resistance at this stage being nearly the same as in the first.

It was in accordance with these properties that in the test of section 3 the temperature of the resistance rods never rose above 100° cent., the period of high resistance being insurmountable by the moderate voltage employed.

To see if, with a higher voltage per unit length, the interval of practical insulation could be bridged, the following experiments were undertaken.

A number of pure portland cement rods were made ⅞ in. in diameter and about 6 in. long. Copper bands which could be clamped around these at any point were used as terminals.

The first experiments were made on 600 volts direct current, the terminals being set at various distances apart down to 0.25 in. Even with this small distance between terminals it was impossible to pass the insulation stage. There would be a violent production of steam for a few seconds, and then no further action. Frequently the rods would crack in two from the high steam pressure produced.

Experiments were next tried using a 25,000-volt, 60-cycle, testing transformer. On account of the small capacity of the generator supplying this, the current available was very small; also the regulation was poor causing a large drop in voltage under load. Tests were made with the terminals on the rods 4 in. apart. The voltage was adjusted to about 8,000 volts at no load. If the rod was quite damp when put on the circuit, the rush of current was usually so great as to open the circuit breaker. When slightly dryer a large current would flow for a short time, lowering the voltage very greatly; at the same time incandescent spots and streaks would form on the rod from which spectacular streams of flame would shoot out a foot or more, continue for a few seconds and then disappear. The voltage would then rise to its no-load value indicating a very high resistance. The experiment could be repeated by soaking the rod in water for a few minutes. But finally a rod was found coming within the capacity of the apparatus. The voltage being thrown on the incandescent streak spread from one terminal to the other, the rod gradually heating up all over. It ran quietly for about a minute, the voltage falling to 2000, and could probably have been kept at incandescence indefinitely had the power been available, but the apparatus beginning to heat, the current had to be cut off. After the rod had cooled, the application of 8000 volts produced no effect, showing that moisture is necessary to start the action. Probably the rods could in all cases have been heated to incandescence had the power been available.

These experiments at 600 and at 8000 volts show that the passing of the period of high resistance is not so much a question of average potential gradient, as of maximum potential available. It is reasonable to suppose that the material becomes conducting in spots, and that the high voltage will concentrate on any high resistance portions.

It is also important to notice that to start the action the initial moisture conductivity is essential.

7. *The properties of cement as a resistance when used in the form of concrete.* As in most cases when portland cement has been used for a resistance in practice it has been mixed with broken stone and sand to make concrete, some further tests were made with this material. The proportions by weight of the material were about as follows:

Edison portland cement	100
Sand	200
Broken limestone from ¾ in. down to powder	100
Broken limestone, 2 in	100
Water	65

This mixture was molded in wooden boxes to form blocks 10 in. by 9. in. by 7.75 in.

Variation of resistance with age. For this a column of six blocks was built up. The blocks were joined together with pure cement mortar, only enough being used to fill up the irregularities. Several strips of sheet iron were placed at the top and bottom for terminals, being bedded in cement mortar. The dimensions of the finished column were 48½ in. between terminals, and 10 in. by 9 in. in cross-section. The blocks being made at different times were from two to three weeks old, and having stood out doors and been soaked with water in setting up the column their condition was rather indefinite. The following table shows the resistance for the first six days after building the column.

Time after buildings, days	Resistance ohms	Specific resistance
0	920	4340
1	898	4230
3	1068	5030
5	1178	3560
6	1177	5555

As would be expected in such a large mass of concrete the change in resistance is very slow.

Behavior of concrete blocks on constant potential circuits. The circuit used for this test was a 2300-volt, 60-cycle lighting circuit. A single block was used, being set up so as to give a length of circuit of 7.75 in. and a cross-section of 10 in. by 9 in.; the terminals as before being strips of sheet iron.

The action in this case was exactly the same as in the test made with the small rods. The current was at first large but fell rapidly as the moisture boiled off, the rod becoming almost an insulator in a short time. Pouring water over it and allowing it to soak in would bring the resistance back more or less to its original value. The action took place so rapidly that it was very difficult to obtain good tests. The following figures will, however, give some idea.

In the first test made, the current started at about 15 amperes and fell in 23 minutes to .2 ampere.

In another test made some months later and when the block was quite dry, the current started at 2 amperes, reached a maximum of 4.4 amperes in 1 minute and fell to one ampere in 3½ minutes.

Summary and conclusions. The tests made with cement rods having different proportions of sand show a progressive increase in resistance with increase in the amount of sand, leading to the conclusion that the sand acts practically as an insulator distributed through the cement, so diminishing the effective cross-section of the rod.

All the experiments on the change in resistance with age or with heating indicate that at moderate temperatures the conductivity depends almost entirely on the amount of contained moisture. It would appear probable that the moisture dissolves a portion of the cement to form an electrolyte which being diffused through the body of the cement conducts the current, the solid part of the cement simply acting as a container for this electrolyte.

The studies of concrete while not as complete appear to agree with these conclusions.

The experiments on resistance at high temperatures and at high voltages show that cement possesses in addition to its low temperature or moisture conductivity a high temperature or pyro-conductivity. Also that a high voltage is able, in some manner to bridge the interval of high resistance and raise the material to incandescence.

A paper to be presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., June 29–July 2, 1908.

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(*Subject to final revision for the Transactions.*)

VOLTAGE RATIO IN SYNCHRONOUS CONVERTERS WITH SPECIAL REFERENCE TO THE SPLIT-POLE CONVERTER

BY COMFORT A. ADAMS

Introduction. The interesting discussion on the split-pole converter at the February New York meeting of the Institute instigated the following paper, which consists of a purely theoretical analysis, the principal object of which is to show how the field distortion of a split-pole converter does not necessarily involve electromotive force distortion.

Incidentally there will be developed a method of analysis by which the direct electromotive force or any one of the alternating electromotive forces is determined analytically from the harmonic analysis of the flux distribution curve, thus establishing a simple and direct connection between the shape of the flux distribution curve, and the shapes as well as the magnitudes of the resulting electromotive forces.

DEFINITIONS

Brush electromotive force and tap electromotive force. The electromotive force between two adjacent commutator brushes will be called the *brush electromotive force* and that between collector rings the *tap electromotive force.*

Belt. In the ordinary closed-coil, two-layer lap winding, a series path between two adjacent brushes or between two adjacent taps, is made up of a set of coils, half of the sides of which, in the tops of slots, form a *belt* of conductors; the other half, in the bottoms of other slots, form a similar *belt*, but connected in the opposite direction. In the wave winding a series path contains as many such sets of coils or pairs of *belts* as there are pairs of poles. With a full pitch winding the two belts of any pair are 180 electrical degrees apart between centers; but less in a fractional pitch winding.

For a series path between brushes the span of each belt is 180 electrical degrees, and for a path between taps the belt span depends upon the number of phases; 180° for the single-phase or diametral connection, 120° for the three-phase, 90° for the quarter-phase, etc. In Fig. 1 is shown the location of a pair of belts forming a path between brushes, for three different values of the coil pitch. The solid lines indicate the top slot belts and the broken lines bottom slot belts. The brushes are also shown, together with the flux distribution curve. The broken curve shows a split-pole distortion.

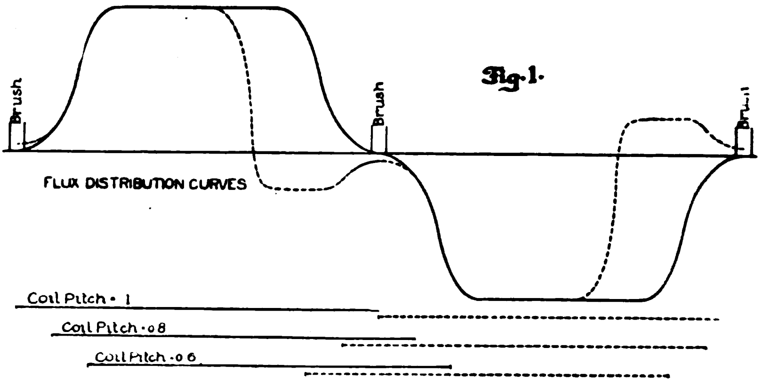


Fig. 1.

Differential-factor. The brush-belts are as a whole stationary, although the individual components thereof are cutting through the flux, each belt remaining under a particular pole so that all of its elements are cutting flux in the same direction; but a tap-belt revolves as a whole and at times lies across parts of two poles, thus generating opposing electromotive forces in the two parts of the belt and reducing the effectiveness of electromotive force generation by introducing what may be called *differential-action.* The average electromotive force induced in this belt is therefore less than that induced in an equal number of active conductors in a brush-belt, and the factor by which it is less will be called the *differential-factor,* since it takes account of the differential cutting of the flux.

A differential action also takes place in the brush-belts, in the case of fractional-pitch windings, or when the brushes are displaced from the neutral points.

Form-factor. The tap voltage differs from the brush voltage induced in the same number of conductors, not only because of the differential action which reduces the average useful electromotive force, but also because the effective or root-mean-square tap voltage differs from the average by a factor called the *form-factor* which depends upon the wave-shape.

If E and E_1 be the brush and the single phase (or diametral) tap electromotive force, respectively, we may write

$$E_1 = k_d \, k_f \, E \qquad (1)$$

where k_d and k_f are the differential- and the form-factor respectively. These two constants are closely connected and are commonly combined into a single constant, but they represent two distinct phenomena which are not inter-dependent, since they may be combined in a great variety of proportions. For example, in the split-pole converter it is possible so to proportion the parts as to change the differential-factor, and therefore the voltage ratio over a wide range without producing much change in the form-factor or the wave-shape.

The writer's present purpose is to show how this can be done.

FLUX DISTRIBUTION CURVE AND SINGLE-CONDUCTOR ELECTROMOTIVE FORCE

Imagine a single conductor to cut through the gap flux at normal speed; the induced electromotive force will be at each instant proportional to the density of flux through which it is cutting, and the resulting electromotive force curve will have the same shape as the *flux distribution curve.* It will be convenient to deal with this elementary electromotive force curve in considering the resultant electromotive force of a whole belt. The elementary electromotive force curve may be expressed algebraically in the form of Fourier's series, thus;

$$\left.\begin{aligned} e' &= a_1 \sin \omega t + a_3 \sin 3\omega t + a_5 \sin 5\omega t + a_7 \sin 7\omega t + \text{ etc.} \\ &+ b_1 \cos \omega t + b_3 \cos 3\omega t + b_5 \cos 5\omega t + b_7 \cos 7\omega t + \text{ etc.} \end{aligned}\right\} \qquad (2)$$

where $\omega = 2\pi n$, and n is the fundamental frequency.

For our present purpose equation (2) may be more conveniently written.

$$e' = a_1 \left| \begin{array}{l} \sin \omega t + q_{a_3} \sin 3\omega t + q_{a_5} \sin 5\omega t + \ldots\ldots \\ \qquad + q_{am} \sin m\,\omega t + \text{etc.} \\ q_{b_1} \cos \omega t + q_{b_3} \cos 3\,\omega t + q_{b_5} \cos 5\,\omega t + \ldots\ldots \\ \qquad + q_{bm} \cos m\,\omega t + \text{etc.} \end{array} \right| \qquad (3)$$

$$\text{where } q_{am} = \frac{a}{a_1} \text{ and } q_{bm} = \frac{b_m}{a_1}$$

RELATION OF BRUSH VOLTAGE TO THE ELEMENTARY OR SINGLE-CONDUCTOR ELECTROMOTIVE FORCE

It will be assumed in what follows that the harmonic analysis of the single-conductor electromotive force was so carried out that the zero of time in equation (3) corresponds to the instant when the conductor in question is passing under one of the brushes.

With this assumption, the brush voltage, which is proportional to the area or to the average value of the elementary electromotive force wave between brushes is

$$E_{dc} = N \frac{2}{\pi} a_1 \left[1 + \frac{1}{3} q_{a_3} + \frac{1}{5} q_{a_5} + \frac{1}{7} q_{a_7} + \frac{1}{9} q_{a_9} + \text{etc.} \right] \qquad (4)$$

or if we designate $\frac{2}{\pi} N a_1$ by E_1

$$E_{dc} = E_1 \left[1 + \frac{1}{3} q_{a_3} + \frac{1}{5} q_{a_5} + \frac{1}{7} q_{a_7} + \ldots \text{etc.} \right] \qquad (4a)$$

where N is the number of conductors in series between brushes.

The cosine terms drop out, since the average value of the cosine over a half cycle beginning with zero, π, or any multiple thereof, is zero. The average value of an odd mth harmonic sine term taken over a half-cycle of the fundamental is $1/m$th of the average value of a half cycle of that term, since the other m-1 half-waves cancel out.

RELATION OF TAP VOLTAGE TO THE ELEMENTARY OR SINGLE-CONDUCTOR ELECTROMOTIVE FORCE

For this purpose write equation (3) as follows:

$$\begin{aligned} e' = a_1 [& q_1 \sin (\omega t + \theta_1) + q_3 \sin (3\,\omega t + \theta_3) \\ & + q_5 \sin (5\,\omega t + \theta_5) + \ \ldots\ q_m \sin (m\,\omega t + \theta_m) + \text{etc.}] \end{aligned} \qquad (5)$$

where $q_m = \sqrt{q_{am}^2 + q_{bm}^2}$, and $\theta_m = \tan^{-1} \frac{b_m}{a_m}$ is measured in mth harmonic radians.

A little consideration will show that q_1 ($= \sqrt{1 + q_{b_1}{}^2}$) does not differ much from unity except in cases of considerable distortion, and that it is equal to unity in the ordinary converter where the flux distribution curve is symmetrical about the center of the pole face, or with the three-part split-pole and symmetrical distortion. A displacement of the brushes would have the effect of increasing q_1.

The electromotive force of a single slot will have the same shape as *c′* and will differ only in magnitude according to the number of conductors per slot. The electromotive force of a given alternating-current belt may be considered as made up of as many components as there are slots per belt, each component being the electromotive force of a single slot and differing in phase from that of an adjacent slot by the electrical angular pitch of the slots.

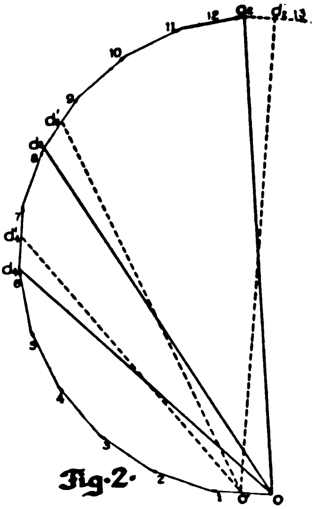


Fig. 2.

Then the electromotive force of the belt will have for its fundamental the vector sum of the fundamentals of the electromotive forces of the several slots of that belt, and for its *m*th harmonic the vector sum of the *m*th harmonics of the slots of that belt; but the phase difference between the latter will be (in harmonic degrees) *m* times as great as that of the fundamentals. For example, Fig. 2 shows the fundamental slot electromotive forces extending over 180 electrical degrees of armature circumference, for a converter with 12 slots per pole, while Fig. 2a shows the corresponding twelve fifth harmonic slot electromotive forces. In both Figs. the electromotive forces are numbered in the order of their respective slots starting at the point o. In Fig. 2, $\overline{o\,d_2}$ is the diametral or 180° fundamental electromotive force, $\overline{o\,d_3}$ the delta or 120° electromotive force and $\overline{o\,d_4}$ the quarter phase or 90° electromotive force. Similarly in Fig. 2a, $\overline{o\,d_2}$ is the vector sum of the twelve fifth-harmonic slot electromotive forces, that is, the 180° fifth harmonic; $\overline{o\,d_3}$ the vector sum of the fifth harmonic electromotive forces of slots numbers one to eight inclusive, that is, the 120° fifth harmonic; and $\overline{o\,d_4}$ the 90° fifth harmonic. A little consideration will show that the ratio of the resultant to the arithmetical sum of the fifth harmonic slot electromotive forces is small as compared with the ratio of the resultant to the arithmetical sum of the fundamental slot electromotive forces. These ratios are the differential-factors for the fifth harmonic and the fundamental respectively, and will be labelled k_{d_5} and k_{d_1}. The quantity

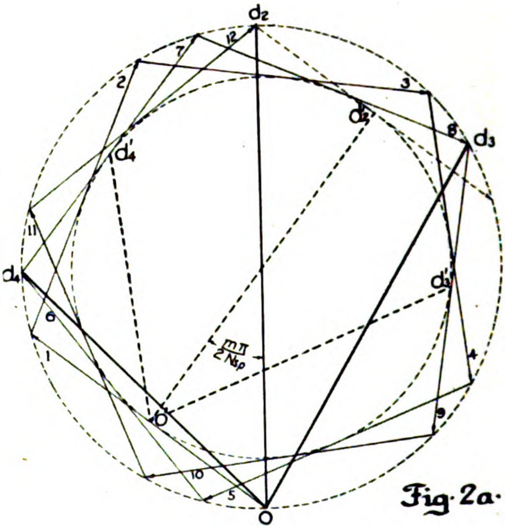


Fig. 2a.

$$k_{r_5} = \frac{k_{d_5}}{k_{d_1}}$$

will be called the fifth harmonic *reduction-factor*, and is the ratio in which the fifth harmonic of the belt electromotive force is reduced from that of the slot electromotive force (or the flux distribution curve); that is, if the amplitude of the fifth harmonic of the slot electromotive force is q per cent. of the fundamental, the amplitude of the fifth harmonic of the belt electromotive force will be $k_{r_5} \times q$ per cent. of its fundamental.

These relations may be generalized as follows:

Let N_{sp} = slots per pole.

and p' = the number of belt spans per electrical circumference, ($p' = 2$ for diametral connection, and 3 for 3 phase delta or 6 phase double delta).

Then $\frac{\pi}{N_{sp}}$ = the phase difference between the fundamental electromotive forces of two adjacent slots.

$\frac{m\,\pi}{N_{sp}}$ = the phase difference between the mth harmonic electromotive forces of two adjacent slots.

and $\frac{2\,N_{sp}}{p'}$ = slots per belt.

The total phase rotation of the mth harmonic in all the slots of the belt will be

$$\frac{m\,\pi}{N_{sp}} \times \frac{2\,N_{sp}}{p'} = \frac{2\,m\,\pi}{p'}$$

and if the diagram (such as Fig. 3) be reduced to unit radius the resultant of the $\frac{2\,N_{sp}}{p'}$ m^{th} harmonics will be $2 \sin \frac{m\,\pi}{p'}$.

On the same basis the m^{th} harmonic of the slot electromotive force is $2 \sin \frac{m\,\pi}{2\,N_{sp}}$ and the arithmetical sum of the $\frac{2\,N_{sp}}{p'}$ m^{th} harmonics is $\frac{2\,N_{sp}}{p'} \times 2 \sin \frac{m\,\pi}{2\,N_{sp}}$

Thus the differential factor for the mth harmonic of the belt electromotive force is

$$k_{dm} = \frac{p'}{2\,N_{sp}} \; \frac{\sin \frac{m\,\pi}{p'}}{\sin \frac{m\,\pi}{2\,N_{sp}}} \tag{6}$$

and that for the fundamental

$$k_{d_1} = \frac{p'}{2\,N_{sp}} \; \frac{\sin \dfrac{\pi}{p'}}{\sin \dfrac{\pi}{2\,N_{sp}}} \tag{7}$$

The reduction-factor for the mth harmonic is then

$$k_{rm} = \frac{k_{dm}}{k_{d_1}} = \frac{\sin \dfrac{m\,\pi}{p'}}{\sin \dfrac{\pi}{p'}} \; \frac{\sin \dfrac{\pi}{2\;N_{sp}}}{\sin \dfrac{m\,\pi}{2\;N_{sp}}} \tag{8}$$

The first factor of the expression for k_{rm} is independent of the number of slots, and its numerical value for various phases and harmonics is shown in Table I.

Table I giving values of $\sin \dfrac{m\,\pi}{p'} \div \sin \dfrac{\pi}{p'}$

TABLE I.

$m =$	3	5	7	9	11	13	15	17	19
$p' = 2$	1	1	1	1	1	1	1	1	1
$p' = 3$	0	1	1	0	1	1	0	1	1
$p' = 4$	1	1	1	1	1	1	1	1	1
$p' = 6$	2	1	1	2	1	1	2	1	1

The second factor of the formula for k_{rm} is independent of p', and its numerical values for various values of N_{sp} and m, are shown in Table II.

Table II giving values of $\sin \dfrac{\pi}{2\,N_{sp}} \div \sin \dfrac{m\,\pi}{2\,N_{sp}}$.

TABLE II.

$N_{sp} =$	8	10	12	14	16	18	20	22	24	26	∞
$m =$ 3	0.351	0.344	0.340	0.338	0.3368	0.3362	0.3358	0.3355	0.3353	0.3351	$\frac{1}{3}$
$m =$ 5	0.235	0.222	0.214	0.2101	0.2081	0.2062	0.2051	0.2042	0.2034	0.2029	$\frac{1}{5}$
$m =$ 7	0.199	0.1755	0.1646	0.158	0.154	0.152	0.150	0.149	0.1477	0.1467	$\frac{1}{7}$
$m =$ 9	0.198	0.158	0.141	0.132	0.126	0.123	0.1208	0.119	0.1177	0.1166	$\frac{1}{9}$
$m =$ 11	0.2345	0.1583	0.1316	0.1185	0.1111	0.106	0.103	0.1009	0.0992	0.0979	$\frac{1}{11}$
$m =$ 13	0.351	0.1755	0.1317	0.1124	0.102	0.961	0.0920	0.08916	0.08702	0.08533	$\frac{1}{13}$
$m =$ 15	0.995	0.2214	0.1413	0.1126	0.0986	0.0903	0.08492	0.0813	0.07865	0.07665	$\frac{1}{15}$
$m =$ 17	1.000	0.3444	0.1644	0.1185	0.0985	0.0875	0.0807	0.0761	0.0729	0.0706	$\frac{1}{17}$
$m =$ 19	0.351	1.000	0.214	0.132	0.100	0.0875	0.0788	0.073	0.069	0.0662	$\frac{1}{19}$

Except for the 3 and 6 phase, third, ninth and fifteenth harmonics, the values in Table II are those of k_{rm}, the reduction-factor, or the ratio of the per cent. harmonic in the tap electromotive force to the per cent. harmonic in the flux distribution curve.

An inspection of Tables I and II shows that for the single-phase or diametral connection and for a very large number of slots per pole, the reduction-factor is one-third for the third harmonic, one-fifth for the fifth harmonic, one-seventh for the seventh harmonic, etc; and that for a moderate number of slots per pole, the only change is a slight increase in the reduction-factor, this increase being greater for the higher harmonics.

Table I shows that for the delta or 120° connection ($p' = 3$), the third, ninth and all other harmonics which are multiples of three, drop out. This may be explained in several ways: first, a third or ninth harmonic would mean a circulating electromotive force around the closed-coil winding, which is impossible if the north and south pole fluxes are similarly distributed, since under this last assumption the electromotive forces of the two halves of the winding must be equal and opposite at each instant; secondly, the differential-factor of the third, ninth or fifteenth harmonic is zero for the 120° connection, since its phase rotation which is 3, 9 or 15 times that of the fundamental (120°), is a multiple of 360°. In other respects than in the disappearance of these harmonics the reduction factor is the same for the 120° as for the 180° connection.

For the quarter phase, or 90° connection, the reduction-factor is exactly the same as for the 180° connection; and for the 60° connection the only difference is that the third, ninth and fifteenth harmonic reduction-factors are doubled instead of being eliminated as in the 120° connection; that is, the reduction-factor for the third harmonic is two-thirds for the 60° connection, in place of one-third for the 180° connection and zero for the 120° connection. The explanation of this is, that with a fundamental phase rotation of 60°, the third harmonic phase rotation is 180°, giving a diameter as resultant, which is relatively twice as great as the 60° chord of the fundamental resultant. The ninth, fifteenth, etc., harmonics would add multiples of 360° to the phase rotation, leaving the resultant a diameter as in the case of the third harmonic.

Fractional-pitch or short-chord windings. Thus far the electromotive force of only a single belt has been considered. If the winding has the full pitch of 180°, the electromotive forces of the two belts of any pair will be in exact phase, and their resultant will have the same shape as the electromotive force of a single belt. But if a *fractional-pitch* or *short-chord* winding be employed, the two belt-electromotive forces will differ in phase by an amount depending upon the pitch deficiency, and their resultant may not have the same shape; in general it will not, unless the two component belt electromotive forces are sinusoidal.

Let λ_c designate the coil pitch in terms of full pitch. Then $1-\lambda_c$ is the pitch deficiency, and $(1-\lambda_c)\pi$ is the phase difference between the fundamental electromotive forces of the two belts; see Fig. 3, where OA and AB are the two equal fundamental electromotive forces and OB their resultant. The differential or pitch reduction-factor for the fundamental electromotive force is

$$\overline{OB} \div (\overline{OA} + \overline{AB}) = \sin \frac{\pi}{2} \lambda_c$$

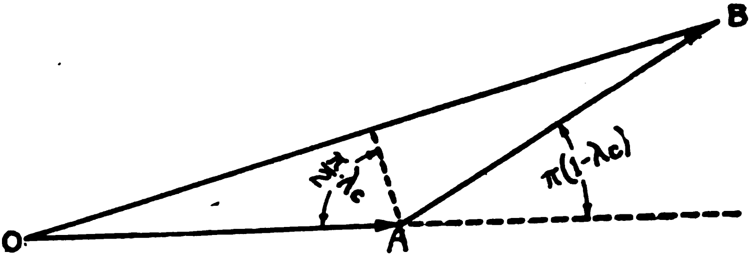


FIG. 3

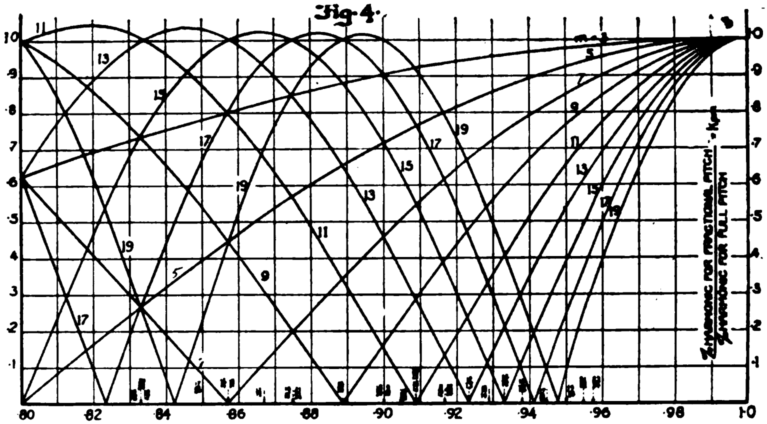
and that for the mth harmonic is $\sin \frac{m\pi}{2} \lambda_c$. The ratio of the latter to the former will be designated the mth harmonic pitch factor, it is

$$k_{pm} = \frac{\sin m \frac{\pi}{2} \lambda_c}{\sin \frac{\pi}{2} \lambda_c} = \frac{\text{per cent. of } m\text{th harmonic in fractional pitch winding}}{\text{per cent. of } m\text{th harmonic in full pitch winding}} \tag{9}$$

This is plotted in Fig. 4 for the odd harmonics up to the nineteenth and for values of the coil pitch from 0.8 to 1.0. From the curves of Fig. 4, it appears that it would be possible to practically wipe out any one of the higher harmonics by a proper choice of pitch, although the reduction necessary to eliminate, say the fifth harmonic, would probably cause serious commutation difficulties. It is interesting to note in this connection that a pitch of 0.833 (10 slots in 12, 15 in 18, 20 in 24) would reduce the fifth, seventh, seventeenth and nineteenth harmonics to about one-quarter of their full pitch values. This would leave for the delta or double delta connections only the eleventh and thirteenth harmonics, since the third, ninth, fifteenth, and twenty-first harmonics are entirely absent in this case.

Fractional slot connection. Thus far it has been assumed that each phase belt comprised a whole number of slots; but it is obvious that this is not at all necessary, for even when the number of slots per pair of poles is a multiple of the number of phases, the taps may be taken off at junctions in the centers of slots. In this case there would be two half-slot electromotive force vectors at the ends of the whole slot vectors. This is shown in Fig. 2 where $\overline{o' d_2'}$, drawn from the middle of slot electromotive force number one to the middle of slot electromotive force number thirteen, is the 180° fundamental resultant, and in Fig. 2a where $\overline{o' d_2'}$ is in the same way the 180° fifth harmonic resultant. Similarly $\overline{o' d_3'}$ and $\overline{o' d_4'}$ are the corresponding resultants for the 120° and 90° electromotive forces.

Fig. 4.



An inspection of Fig. 2a will show that this mid-slot connection has reduced the resultant harmonic by the factor, $\cos \frac{m \pi}{2 N_{sp}}$ which approaches zero as m and N_{sp} approach equality. Thus if N_{sp} is large, some of the higher harmonics are practically wiped out by this mid-slot connection, and if N_{sp} is small all of the lower harmonics are reduced and some intermediate ones almost eliminated.

For other fractional slot connections the reduction is less. Designate the fractional slot reduction-factor by k_{sm} and it is:

$$k_{sm} = \left\{ \begin{array}{l} \cos \dfrac{m\pi}{2N_{sp}} \text{ (for half-slot connection).} \\[2ex] \cos \dfrac{m\pi}{2N_{sp}} \div \cos \dfrac{m\pi}{6N_{sp}} \text{ (for a one-third or a two-thirds slot connection} \\[2ex] \cos \dfrac{m\pi}{2N_{sp}} \div \cos \dfrac{m\pi}{4N_{sp}} \text{ (for a one-fourth or a three-fourths slot connection.} \end{array} \right\} \quad (10)$$

If the two taps which terminate a given pair of belts, are taken, one from a mid-slot point and one from an interslot point, the slot reduction factor would lie between that for the mid-slot connection and unity.

The mid-slot connection is practically equivalent to a fractional pitch winding, the pitch deficiency of which is larger the smaller the number of slots per pole.

Combining equations (8), (9) and (10) gives as the final ratio of the *m*th harmonic of the induced electromotive force, to that of the single conductor electromotive force or flux distribution curve,

$$k_m = k_{rm} \times k_{pm} \times k_{sm} = \frac{\sin \frac{m\pi}{2}\lambda_c}{\sin \frac{\pi}{2}\lambda_c} \times \frac{\sin \frac{m\pi}{p'}}{\sin \frac{\pi}{p'}} \times \frac{\sin \frac{\pi}{2N_{sp}}}{\sin \frac{m\pi}{2N_{sp}}} \times k_{sm} \quad (11)$$

Equation (10) includes the effects of all the thus-far-considered factors upon the *magnitudes* of the harmonics.

Consider now the phases of the harmonics.

Phases of harmonics. Referring to Figs. 2 and 2a, the total phase rotation of the fundamental is $\frac{2\pi}{p'}$. Thus the phase of the fundamental of the resultant or belt electromotive force with respect to the fundamental of the electromotive force of slot

No. 1 is, in fundamental radians

$$\alpha_1 = \frac{\pi}{p'} - \frac{\pi}{2\,N_{sp}} = \pi\left(\frac{1}{p'} - \frac{1}{2\,N_{sp}}\right)$$

The total phase rotation of the mth harmonic is $\frac{2\,m\,\pi}{p'}$

Let w = nearest whole number less than $\frac{m}{p'}$ and

w_s = " " " " " $\frac{m}{2\,N_{sp}}$

Then the equivalent phase rotation of the mth harmonic is $2\,\pi\left(\frac{m}{p'} - w\right)$ and the phase of the mth harmonic of the resultant or belt electromotive force with respect to the mth harmonic of the electromotive force of slot No. 1 is, in mth harmonic radius

$$\alpha_m = \pi\left(\frac{m}{p'} - w\right) - \pi\left(\frac{m}{2\,N_{sp}} - w_s\right)$$

$$= \pi\left[m\left(\frac{1}{p'} - \frac{1}{2\,N_{sp}}\right) - (w - w_s)\right]$$

or in fundamental radians

$$\alpha_m{}' = \pi\left[\left(\frac{1}{p'} - \frac{1}{2\,N_{sp}}\right) - \left(\frac{w - w_s}{m}\right)\right]$$

Thus in passing from the slot electromotive force to the resultant or belt electromotive force, the relative phase of the mth harmonic with respect to the fundamental is changed by an amount which is, in fundamental radians

$$\beta_m = \alpha_m - \alpha_1 = -\frac{\pi}{m}\,(w - w_s) \qquad (12)$$

or, in mth harmonic radians,

$$\beta_m = m\,(\alpha_m{}' - \alpha_1) = -\,\pi\,(w - w_s) \qquad (13)$$

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But w and w_s are whole numbers and β_m is therefore always a multiple of π. Moreover w_s is practically always zero, since when

$$m = 2 N_{sp}$$

the harmonic is so small as to be wholly negligible. With this assumption, β_m is zero when w is even, and π when w is odd. That is, when w is odd the mth harmonic of the belt electromotive force is reversed in phase as compared with the same harmonic in the slot electromotive force.

For example, consider a slot electromotive force which consists of a fundamental and a prominent third harmonic; follow this harmonic into the various belt electromotive forces.

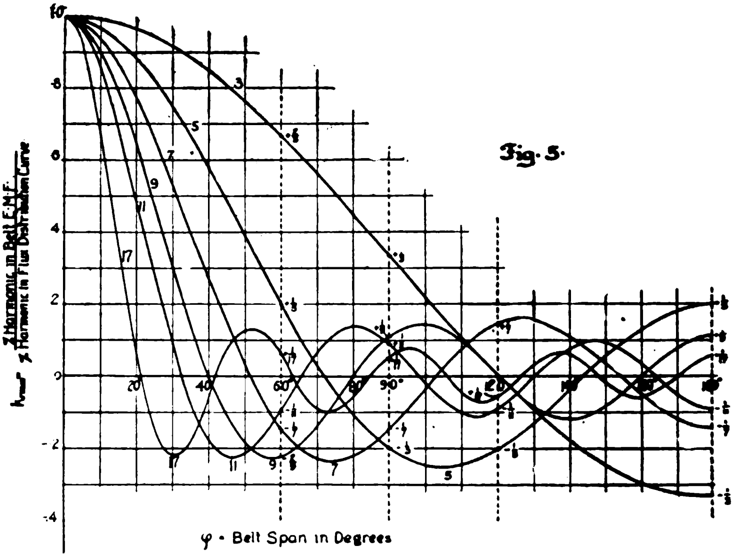


Fig. 5.

For the single phase or diametral connection, $p' = 2$ and $w = 1$. Thus the third harmonic is *inverted* as well as being reduced to one-third of the percentage value which it had in the slot electromotive force. That is, if the slot electromotive force be flat topped, the 180° electromotive force will be peaked and vice versa, but less so than the slot electromotive force.

For the three-phase or delta connection, $p' = 3$ and $w = 1$; but the amplitude of the third harmonic in the 120° electromotive force is zero.

For the quarter-phase or 90° connection, $p' = 4$ and $w = 0$; therefore the third harmonic is not reversed, but is merely reduced to one-third of its slot percentage. That is, if the slot electromotive force be peaked, the 90° electromotive force will be peaked but less so; and if the slot electromotive force be flat topped, the 90° electromotive force will be flat topped but less so.

For the six-phase connection, $p' = 6$ and $w = 0$. The third harmonic is not reversed and is reduced to two-thirds of its slot percentage.

Follow this third harmonic from the six-phase back through the four, three, and two (single) phase. It is relatively large (two-thirds) and positive in the six-phase, reduced to one-third in the quarter-phase, vanishes in the three-phase, and reappears inverted in the single-phase with a relative value of one-third.

Follow the fifth harmonic in the same way. In the 60° belt it is positive and of one-fifth magnitude; in the 72° belt zero; in the 90° belt inverted and of one-fifth magnitude; the same in the 120° belt, having passed through a maximum between these last two points; and one-fifth positive again in the 180° belt. It thus appears that the change of belt span alters the magnitude but not the phases of the harmonics.

In order to see this relation more clearly, start with the flux distribution curve or the single-conductor electromotive force, assume an infinite number of slots and imagine the belt span to be increased gradually. The per cent. magnitude of any harmonic will gradually decrease through zero to a negative maximum, then back again to a positive maximum, etc., without any other change of phase than that involved in reversal. If the angle of belt span be designated by ϕ, the reduction factor for this case of an infinite number of slots will be

$$k_{rm}\infty = \frac{1}{m} \sin \frac{m\phi}{2} \div \sin \frac{\phi}{2} \qquad (14)$$

Values of $k_{rm}\infty$ for several harmonics and for all values of belt span up to 180° are shown plotted in Fig. 5. These curves are instructive as showing clearly the general relation between belt span and the relative magnitudes of the several harmonics, although they do not take account of the number of slots per pole.

Negative values of $k_{rm}\infty$ indicate that the harmonic is inverted.

TAP VOLTAGE.

Adopting the notation of equation (5) the *m*th harmonic of any tap electromotive force may be completely expressed thus:

$$k_m q_m \sin(m \omega t + \theta_m + \pi w),$$

where w is as already defined, and k_m is given by equation (11).

The amplitude of the fundamental of the tap voltage is

$$a_{t_1} = k_{d_1} \frac{2N}{p'} q_1 a_1$$

where N is the number of conductors in series between brushes, $\frac{2N}{p'}$ the number of conductors in series between taps, $q_1 a_1$ the amplitude of the fundamental of the single conductor electromotive force and k_{d_1} the fundamental differential-factor, which, for all practical purposes, may be taken as equal to $\frac{p'}{\pi} \times \sin \frac{\pi}{p'}$, the limiting value of equation (7) as N_{sp} approaches infinity. The amplitude of the tap voltage fundamental is then

$$a_{t_1} = \frac{2}{\pi} N_{a_1} q_1 \sin \frac{\pi}{p'} = q_1 E_1 \sin \frac{\pi}{p'} \qquad (15)$$

and the complete tap voltage is

$$e_t = q_1 E_1 \sin \frac{\pi}{p'} [\sin \omega t + k_3 q_3 \sin(3 \omega t + \theta_3 + \pi w)$$
$$+ k_5 q_5 \sin(5 \omega t + \theta_5 + \pi w) + \text{etc.}] \qquad (16)$$

A consideration of the value of w or of the curves of Fig. 5 will show that in the 180° electromotive force the third, seventh, eleventh, etc., harmonics are reversed; that in the 120° electromotive force, the third, ninth, fifteenth, etc., harmonics vanish and the fifth, eleventh, seventeenth, etc., harmonics are reversed; and that in the 60° electromotive force the seventh, ninth and eleventh, the nineteenth, twenty-first and twenty-third, etc., harmonics are reversed.

To reduce these to a more specific basis assume the case of a 60-cycle converter with twelve slots per pole. Then

$$e_{t-180} = q_1 E_1 [\sin \omega t - 0.34\, q_3 \sin (3\, \omega t + \theta_3) + 0.214\, q_5 \sin (5\, \omega t + \theta_5) - 0.165\, q_7 \sin (7\, \omega t + \theta_7) + 0.141\, q_9 \sin (9\, \omega t + \theta_9) - 0.1316\, q_{11} \sin (11\, \omega t + \theta_{11}) + 0.1317\, q_{13} \sin (13\, w t + \theta_{13}) - 0.1413\, q_{15} \sin (15\, \omega t + \theta_{15}) + 0.164\, q_{17} \sin (17\, \omega t + \theta_{17}) - 0.214\, q_{19} \sin (19\, w t + \theta_{19})\ \ldots + \text{etc.}] \tag{17}$$

$$e_{t-120} = 0.866\, q_1 E_1 [\sin \omega t - 0.214\, q_5 \sin (5\, \omega t + \theta_5) + 0.165\, q_7 \sin (7\, \omega t + \theta_7) - 0.1316\, q_{11} \sin (11\, \omega t + \theta_{11}) + 0.1317\, q_{13} \sin (13\, \omega t + \theta_{13}) - 0.164\, q_{17} \sin (17\, \omega t + \theta_{17}) + 0.214\, q_{19} \sin (19\, \omega t + \theta_{19})\ \ldots + \text{etc.}] \tag{18}$$

$$e_{t-60} = 0.5\, q_1 E_1 [\sin \omega t + 0.68\, q_3 \sin (3\, \omega t + \theta_3) + 0.214\, q_5 \sin (5\, \omega t + \theta_5) - 0.165\, q_7 \sin (7\, \omega t + \theta_7) - 0.282\, q_9 \sin (9\, \omega t + \theta_9) - 0.1316\, q_{11} \sin (11\, \omega t + \theta_{11}) + 0.1317\, q_{13} \sin (13\, \omega t + \theta_{13}) + 0.283\, q_{15} \sin (15\, \omega t + \theta_{15}) + 0.164\, q_{17} \sin (17\, \omega t + \theta_{17}) - 0.214\, q_{19} \sin (19\, \omega t + \theta_{19}) + \text{etc.} \ldots] \tag{19}$$

With a larger number of slots per pole such as would be employed for a 25-cycle converter, the harmonic coefficients would be reduced, especially for the higher harmonics, see Table II page 000. It is interesting to note that with as small a number of slots per pole as here assumed, 12, the reduction, factor does not continue to decrease indefinitely as m increases but actually begins to increase from the thirteenth harmonic up. Also its value for the nineteenth harmonic is more than one-fifth, or three times its value when $N_{sp} = 24$.

It is thus possible to determine easily and accurately any tap voltage, from the harmonic analysis of the flux distribution curve. It is obviously much easier to determine the harmonics of the flux distribution curve with a given degree of accuracy, than it is to determine those of the resultant electromotive force wave, since the former are several times larger than the latter.

Root mean square tap voltage. This is obviously,

$$E_t = \frac{q_1 E_1}{\sqrt{2}} \sin \frac{\pi}{p'} \sqrt{1 + k_3^2 q_3^2 + k_5^2 q_5^2 + k_7^2 q_7^2 + \text{etc.}} \tag{20}$$

or, for the special case of twelve slots per pole

$$E_{180} = 0.707\, q_1 E_1 \sqrt{1 + 0.116\, q_3^2 + 0.0458\, q_5^2 + 0.027\, q_7^2 + 0.0199 q_9^2\ 0.073\, q_{11}^2 + 0.0173\, q_{13}^2 + 0.02\, q_{15}^2 + 0.027\, q_{17}^2 + 0.0458\, q_{19}^2 + \quad \text{etc.}} \tag{21}$$

$$E_{120} = 0.613\, q_1\, E_1 \sqrt{1 + 0.0458\, q_5^2 + 0.027\, q_7^2 + 0.0173\, q_{11}^2 + 0.0173\, q_{13}^2 + 0.027\, q_{17}^2 + 0.0458\, q_{19}^2 + \ldots \text{etc.}} \tag{22}$$

$$E_{60} = 0.354\, q_1\, E_1 \sqrt{1 + 0.462\, q_3^2 + 0.0458\, q_5^2 + 0.027\, q_7^2 + 0.0795 q_9 + 0.0173\, q_{11}^2 + 0.0173\, q_{13}^2 + .08\, q_{15}^2 + 0.027\, q_{17}^2 + 0.0458\, q_{19}^2 + \text{etc.}} \tag{23}$$

VOLTAGE RATIO

The ratio of brush voltage to tap voltage is obtained from equations (4a) and (20). It is

$$K_{bt} = \frac{E_{dc}}{E_t} = \frac{\sqrt{2}}{q_1 \sin \frac{\pi}{p'}} \times \frac{(1 + \frac{1}{3} q_{a3} + \frac{1}{5} q_{a5} + \frac{1}{7} q_{a7} + \text{etc.} \; . \; . \; .)}{\sqrt{1 + k_3^2 q_3^2 + k_5^2 q_5^2 + k_7^2 q_7^2 + \text{etc}}} \tag{24}$$

or

$$K_{bt} = \frac{\sqrt{2}}{q_1 \sin \frac{\pi}{p'}} Kq \tag{25}$$

where

$$K_q = \frac{(1 + \frac{1}{3} q_{a3} + \frac{1}{3} q_{a3} + \frac{1}{5} q_{a5} + \text{etc.})}{\sqrt{1 + k_3^2 q_3^2 + k_5^2 q_5^2 + k_7^2 q_7^2 + \text{etc.}}} \tag{26}$$

THREE-PART POLE.

With a normal flux distribution curve, or with a three-part pole and symmetrical distortion, the q_b's are zero, $q_1 = 1$ and $q_m = q_{am}$. The denominator of K_p will differ little from unity, being always a little greater; for example, with a 30 per cent. third harmonic the denominator is 1.005; with a 15 per cent. third, a 15 per cent. fifth and a 15 per cent. seventh harmonic, the denominator is about 1.002. The numerator, on the other hand, may differ considerably from unity on either side according as the q_a's are positive or negative. With a normal undistorted flux distribution the numerator will be slightly less than unity, and K_{bt} will be slightly less than as given by the usual approximate formula. Any variation in the q_a's, due to a symmetrical distortion, causes a variation in the voltage ratio; but it will also produce a variation in the harmonics of the tap electromotive forces. The relation between these two variations in the case of symmetrical distortion will next be considered.

Assume that the flux distribution curve is completely under control; start with a sinusoidal distribution and add harmonics. First add a third harmonic which will be in phase with or in exact opposition to the fundamental, since for a symmetrical distortion $q_{b_3} = 0$; that is $q_3 = q_{a_3}$. Also assume $N_{sp} = 24$, and a winding of full pitch with interslot connections. Then

$$K_{q_3} = \frac{1 + \frac{1}{3} q_{a_3}}{\sqrt{1 + 0.112\, q_{a_3}^2}}$$

and the corresponding harmonic in the tap electromotive forces is $k_3\, q_{a_3}$ which is $0.335\, q_{a_3}$ for the 180° electromotive force and zero for the 120° electromotive force.

In curve 3 of Fig. 6, K_{q_3} is shown plotted against $k_3\, q_{a_3}$ for the case in hand; that is, the curve shows the per cent. change in the voltage ratio corresponding to various per cent. magnitudes of the third harmonic in the 180° electromotive force. This harmonic appears with the same per cent. magnitude in the 90° electromotive force and with double this magnitude in the 60° electromotive force, but vanishes in the 120° electromotive force.

The per cent. magnitude of the third harmonic in the flux distribution curve is approximately three times that in the 180° tap voltage.

Curves 7, 11 and 17, of Fig. 6, show for the seventh, eleventh and seventeenth harmonics the same relation as is shown in curve 3, for the third harmonic.

From these curves it is evident that the several harmonics are almost equally effective in changing the voltage ratio; that is, for a given change in voltage ratio, the resulting harmonic in the tap voltage is of practically the same magnitude whether it be third, fifth, seventh, or higher. It should be noted, however, that to obtain a given change in voltage ratio by means of the higher harmonics, requires a much greater distortion of the flux distribution curve than by means of the lower harmonics, although the resulting electromotive force distortion is approximately the same in the two cases. For example, referring to Fig. 6, to change K_q from 1.0 to 0.9 by the third harmonic, requires a 10 per cent. third harmonic in the 180° electromotive force, which means a 30 per cent. third harmonic in the flux distribution curve; but to produce the same change in K_q by the seventeenth harmonic requires a 12 per cent. seventeenth harmonic in the 180° electromotive force, and $\left(\frac{12}{k_m} =\right)$ 165 per cent. seventeenth harmonic in the flux distribution curve. Such a distortion is out of the question, in fact it is quite obvious that the higher harmonics play a very small part in the voltage ratio or in the distortion of the tap voltage.

Consider now the effect of a combination of harmonics, which corresponds more nearly to the actual conditions. The q_a's must all be of the same sine in order to produce the maximum effect upon K_q for a given electromotive force distortion, and in that case they will have practically the same effect as a single harmonic producing the same electromotive force distortion. For example, consider the following combinations:

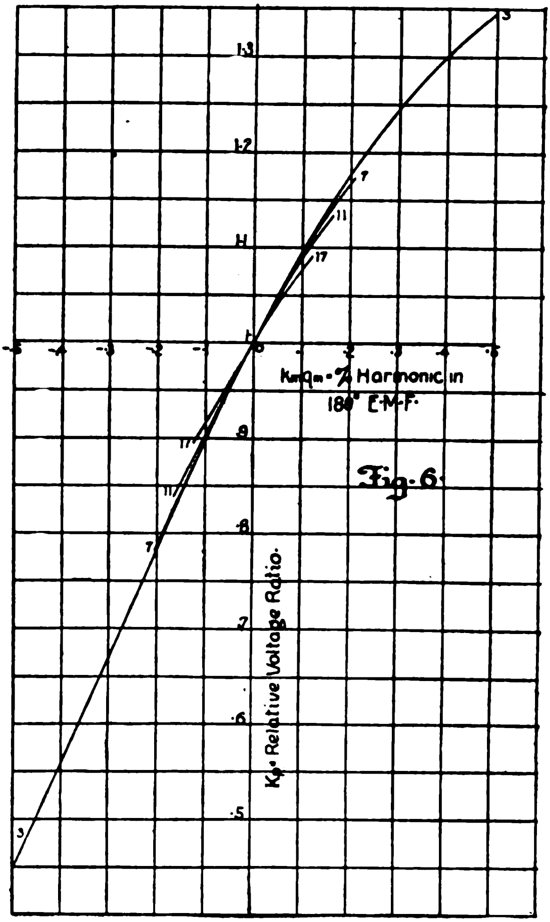


Fig. 6.

(a), $q_{a_3} = 0.60$; and (b), $q_{a_3} = 0.21$, $q_{a_5} = 0.35$, and $q_{a_7} = 0.396$. For (a), $k_3\, q_{a_3} = 0.201$ and $K_q = \dfrac{1.2}{1.02} = 1.177$; for (b), $k_3\, q_{a_3} = 0.0704$, $k_5\, q_{a_5} = .0711$, $k_7\, q_{a_7} = 0.0585$, $\sum k_m\, q_{am} = k_3\, q_{a_3} + k_5\, q_{a_5} + k_7\, q_{a_7} = 0.20$ and $K_q = \dfrac{1.197}{1.007} = 1.188$. Thus for the same total per cent. (0.20) of harmonics, the per cent. variation of voltage ratio is about the same in the two cases.

It might appear that in the case of several harmonics their maxima would not coincide at any point, and that therefore the "sine deviation" would be less for the same total per cent. of harmonics than in the case of a single harmonic; but if the q_a's are all of the same sign, the harmonics in the 180° electromotive force will be alternately inverted and the central maxima will all coincide, giving the same sine deviation as for a single harmonic.

If the q_a's are not all of the same sine the variation in K_q will be appreciably reduced for a given total per cent. of harmonics.

Thus with symmetrical distortion of the flux curve, the q_a's, in order to produce the largest variation in K_q for a given electromotive force distortion, must all be of the same sign; but it makes little difference which harmonics are used.

Starting with a sinusoidal flux curve, the per cent. change in voltage ratio is of about the same magnitude as the total per cent. of harmonics in the 180° electromotive force. But the normal undistorted flux distribution is not sinusoidal. Its harmonics are not large, however, the largest being a negative fifth harmonic of not more than ten or fifteen per cent., which means a fifth harmonic of not more than two or three per cent. in the 180° electromotive force. This would correspond to a point on the curves of Fig. 6, slightly below the origin. Starting thus with negative harmonics in the flux distribution curve, the addition of positive harmonics would, for a given change in K_q, give a more nearly sinusoidal 180° electromotive force than would the addition of more negative harmonics; that is, for a given range in K_q, the least electromotive force distortion occurs when the mean value of K_q is unity or slightly less.

For example, for a total range of 20 per cent. variation in K_q, the least possible harmonics will be about 10 per cent., provided a full pitch winding and interslot connections be employed. With a fractional pitch winding, mid-slot connections, or both, this may be reduced according to the winding pitch and the harmonics employed, see Fig. 4. If it were possible to employ only fifth and seventh harmonics, and if commutation requirements did not prevent the use of a coil pitch as low as 0.83, the two harmonics in question would be reduced to about one-fourth of their full pitch values or to about 2.5 per cent. of the fundamental in the 180° electromotive force. As a matter of fact the fifth harmonic is naturally the most prominent one in a three-part pole symmetrical distortion, and it is not difficult to avoid a large third harmonic, but the use of the fifth harmonic involves much more flux distortion for the same change in voltage ratio, as has already been pointed out.

With the 120° connection the third harmonic disappears, but the fifth harmonic has the same value as in the 180° electromotive force. It is thus less advantageous to use the 120° connection with a three-part pole than with a type of distortion in which the third harmonic predominates.

TWO-PART POLE.

In this case the distortion results in a lateral shifting of the center of gravity of the flux wave and an introduction of cosine terms into the equation for the single conductor electromotive force (equation 3); that is, the q_b's are no longer zero and at least some of the q's are larger than the corresponding q_a's. Unless the q_b's are very large, they will not affect the denominator of K_q (equation 26) appreciably, and K_q will be only a very little smaller than when the q_b's are zero, the same q_a's assumed. But the increase in the q's will increase the per cent. harmonics in the tap voltage, corresponding to a given K_q.

A little consideration will show that one of the principal cosine terms introduced by the lateral distortion here considered, is that of the fundamental, and that, therefore q_1 ($= \sqrt{1 + q_{b_1}{}^2}$) is no longer unity and constant, but increases with the distortion. Thus the first factor in the expression for the voltage ratio, K_{bt} (equation 24), decreases with increasing distortion owing to the increase of q_1. If at the same time the q_a's have been increasing positively the two effects will tend to neutralize, but if the q_a's are decreasing, the two effects are in the same direction and it is obviously possible to obtain a greater change in voltage ratio for a given total per cent. of harmonics in the 180° tap electromotive force than with the symmetrical distortion. Moreover, it will be remembered that q_m is the amplitude of the mth harmonic of the flux distribution curve in terms of a_1, the amplitude of the fundamental sine term; but the real measure of distortion is the amplitude of the harmonic in terms of the whole fundamental; it is, therefore,

$$q_m \div q_1 = \sqrt{q_{am}^2 + q_{bm}^2} \div \sqrt{1 + q_{b_1}^2}$$

which may be considerably smaller than q_m, and $\frac{k_m\, q_m}{q_1}$ the real per cent. harmonic may be considerably smaller than $k_m\, q_m$. For example it is quite possible to shift the center of gravity of the flux distribution curve by 40°, which means that q_1 is about 1.3 and that the mth harmonic in the 180° electromotive force is 0.77 $k_m\, q_m$.

It may be instructive at this point to compare the two-part pole lateral distortion with a shifting of the brushes and a fixed flux distribution. Assume the latter to be sinusoidal, imagine the brushes to be shifted by an angle β and disregard commutation difficulties. Imagine the flux distribution curve to be subdivided into two components, one in space phase with the new brush position and in magnitude proportional to cos β, and the other in quadrature with the brush position and proportional to sin β. The brush voltage and therefore the voltage ratio will be reduced by the factor cos β, but there will be no harmonics in the flux distribution curve or in any of the tap voltage waves. This may be described as a method of altering the differential factor of the brush voltage without changing or distorting the tap voltage.

Were it not for commutation difficulties, this would be an ideal method of varying the voltage ratio of converters. The case of extreme two-part pole distortion such as shown in Fig. 7 looks very much like a shift of brushes with notches cut in the flux curves for commutation purposes.

It is thus obvious that the two-part pole distortion affects the voltage ratio in quite a different way from that of the symmetrical distortion, and that this way does not necessarily involve such serious harmonics in the resulting electromotive force wave. This difference may be most easily specified by means of equation 25: the symmetrical distortion affects the voltage ratio only through K_q, and there is a fairly definite minimum electromotive force distortion involved in a given change in K_q; but the lateral distortion affects the voltage ratio mostly through q_1, and were it not for the necessity of the brush notch in the flux curve, K_q might be kept nearly constant and the harmonics largely eliminated. Unfortunately the necessity for the notch or weak field at the brush position does introduce some harmonics but the worst of these is usually the third, and it can be eliminated by employing the double delta connection, or a diametral connection with the transformer primaries connected in star.

There appears to be in the case of the two-part pole, no simple method of determining the minimum electromotive force distortion corresponding to a given change in voltage ratio, but it is evident from the above analysis that it may be considerably less than with the symmetrical distortion of a three-part pole.

As an example consider Fig. 7, which shows a flux distribution curve for extreme distortion calculated from the dimensions of an actual machine. A rough harmonic analysis of this curve gives the following constants.

Table III.

$m =$	1	3	5	7	9	11	13	15
$q_{am} =$	1.	0.417	+0.0438	+0.0353	−0.1446	+0.01434	+0.0522	−0.026
$q_{bm} =$	+0.822	0.268	−0.359	+ .0093	−0.0084	−0.064	+0.069	−0.043
$q_m =$	1.295	0.495	0.362	0.0364	0.145	0.0657	0.0827	0.0503
$180° k_m =$	1.	0.3353	0.2034	0.1477	0.1177	0.0992	0.087	0.0786
$180° \frac{k_m q_m}{q_1}$	1.	0.128	0.0568	0.00415	0.0132	0.005	0.0058	0.00305
$120° \frac{k_m q_m}{q_1}$	1.	0	0.0568	0.00415	0	0.005	0.0058	0

k_m is taken for full pitch winding, interslot connections 24 slots per pole, and 180° taps. $k_m\, q_m \div q_1$ is the per cent. harmonic in the tap electromotive force.

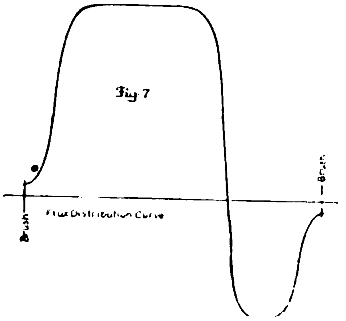
There are doubtless higher harmonics of appreciable magnitude, but they do not influence the quantities with which we are at present interested. The voltage ratio is (from equation 24)

$$\frac{E_{dc}}{E_{t-180^{\circ}}} = \frac{\sqrt{2}}{q_1} \; \frac{(1 + \frac{1}{3} q_{a3} + \frac{1}{5} q_{a5} + \text{etc.})}{\sqrt{1 + k_3^2\, q_3^2 + k_5^2\, q_5^2 + \text{etc.}}}$$

$$= \frac{\sqrt{2}}{1.295} \; \frac{0.862}{1.016} = \sqrt{2} \times 0.655$$

This ratio is less than two-thirds of the ratio for a sinusoidal flux distribution central between brushes, and just about two-thirds of the ratio with a normal undistorted field. Taking this as the no-load ratio, the increase when the auxiliary pole is fully excited in the positive direction, will be 50 per cent. or the decrease in this ratio for the reverse change will be about 33 per cent.

The total of harmonics in the 180° electromotive force is 21.6 per cent. and in the 120° electromotive force only 7.2 per cent. both of which are considerably less than is possible for the three-part pole and an equal variation in voltage ratio. But it is quite possible that a more careful design of pole faces might result in a yet lower per cent. of harmonics. For example, an increase in the width of the auxiliary pole would decrease the fifth harmonic and thus the per cent. harmonics in the 120° electromotive force.



The above figures are for full pitch winding and interslot connection. With mid-slot connections and a coil pitch of twenty-three slots the per cents. are reduced to 19 and 6 respectively, and sufficient reduction of pitch would practically wipe out all the harmonics from the 120° electromotive force and all those of the 180° electromotive force except the third. But the conditions cited in this example are extreme and it is quite possible, with a reasonable range of voltage ratio, to reduce the harmonics in the 120° electromotive force to very low figures without employing a coil pitch so low as to endanger commutation. Moreover, these harmonics are of the induced electromotive force and will not appear in full magnitude at the transformer primaries since they will be partly consumed by the small harmonic currents, flowing through the reactance of armature and transformers.

Damping. Mr. Lincoln stated in his discussion at the February New York meeting that the result of the harmonics in the induced electromotive force would be harmonic currents which would react upon the field in such a way as partly to prevent the otherwise flux distortion, and thus require greater unbalancing of excitation. This is true, but the use of low resistance squirrel-cage dampers would preserve a constant flux distribution and would relieve the circuit of any considerable damping currents.

Commutation. It might seem at first sight that commutation in a field such as shown at the brushes in Fig. 7, would not be satisfactory, but if the direction of rotation of the armature be taken away from the auxiliary poles the armature magnetomotive force will at least partly neutralize the field magnetomotive force in the commutation zone, and the commutation may be even better at some loads than under ordinary conditions. It should be remembered, however, that at full load when the armature magnetomotive force is the greatest the polarity of the auxiliary pole is normal and there is no flux to neutralize, and that at light or no load when the auxiliary pole is reversed as in Fig. 7, the armature current is very small and the flux to be reversed is a maximum. But with a sufficiently low reactance voltage a little flux (more or less) in the commutating zone is comparatively harmless.

In this connection it is interesting to note that a machine with a short air-gap and a weak field would probably have better commutation under conditions of extreme distortion, since the armature magnetomotive force would then even at light load, be able to materially reduce the flux in the commutation zone. A saturation of pole tips would also be an aid to this end as well as to the end of eliminating some of the higher harmonics from the flux distribution curve.

The extent to which the winding pitch can be reduced without endangering commutation depends upon many details of design such as reactance voltage, width of brush, length of air-gap, etc., and can only be determined satisfactorily by experiment; the writer therefore hesitates to make a bold guess, although if forced he would place the lower limit at 90 per cent. under reasonably favorable conditions.

Summary. With the 180° connection and a large number of slots, an *m*th harmonic in the flux distribution appears in the tap electromotive force, but reduced to about 1/*m*th of its per cent. value. Thus the higher harmonics rarely appear in the tap electromotive force unless they are very large in the flux distribution curve. Moreover, the higher harmonics are of little value in changing the voltage ratio, (see equation 24), so that they need have little consideration.

With the 120° connection the third, ninth, fifteenth, etc., harmonics do not appear in the tap electromotive force, and there will be no corresponding harmonic currents set up. This assumes that the flux distribution curves under north and south poles are exactly alike, otherwise there may be a third harmonic even in the 120° electromotive force.

With the diametral connection and the transformer primaries star connected, these harmonics do not appear in the line electromotive force nor their currents in the line.

With three-part poles and symmetrical distortion, there is a definite minimum per cent. of electromotive force harmonics for a given range of voltage ratio and as in this case the fifth harmonic is usually the most prominent (especially with equal part poles), less advantage can be taken of the fact that the third harmonic vanishes in the 120° electromotive force.

With two-part poles, the total per cent. of electromotive force harmonics for a given range of voltage ratio, may be made considerably less than for the symmetrical distortion, and as the third harmonic is naturally predominant in this case, the employment of the 120° connection, or of the 180° connection with star-connected transformer primaries, may result in the practical elimination of electromotive force or current harmonics.

The conditions in this respect may be still farther improved by the use of mid-slot connections and a fractional pitch winding, as far as the latter is consistent with good commutation.

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GRAPHICAL TREATMENT OF THE ROTATING FIELD

BY R. E. HELLMUND

The object of this paper is to evolve diagrams by means of which nearly all the phenomena of the rotating field may be easily studied, and the various factors necessary for the calculation of fluxes, exciting current, etc., exactly determined. In order to avoid too frequent repetition of certain expressions, the author has adopted the expedient of using the words "addition" and "subtraction" to mean geometrical addition and subtraction of vectors according to the well-known conventional method.

The derivation of a two-phase winding with four slots per pole per phase as represented in Fig. 1 may be chosen. The two vectors A and B in Fig. 2 represent the total ampere-turns of the two phases a and b. Under this assumption the ampere-turns of one of the 8 coils of each phase may be represented by one-eighth of each of the two vectors. In Fig. 1 the coils of phase a are numbered from $1a$ to $8a$, those of phase b from $1b$ to $8b$. As in any similar winding the current flows in four coils of each phase in one direction and in the other four coils of the same phase in the opposite direction; the difference of flow is indicated in Fig. 1 by + and – signs in front of the number of the coil.

1. *Diagram of the fluxes in the individual teeth.* Consider, first, tooth number 2. It is seen from Fig. 1, that the coils $-3a$, $-4a$, $+5a$, $+6a$, $+1b$, $+2b$, $+3b$, and $+4b$ exert a magnetizing effect upon this tooth. The effects of the coils $-3a$, $-4a$, $+5a$, and $+6a$ neutralize each other, and therefore the resultant magnetizing effect is in phase with the ampere-turns b and equal to four-eighths of b. The resultant mag-

netizing effect may therefore be represented by the vector 0.2 Fig. 3, which is equal to four-eighths of *b* and parallel thereto. Passing from tooth 2 to tooth 3, it will be seen that the magnetizing effect of coil −4*a* must be subtracted and that of coil +7*a* be added in order to obtain the resultant magnetizing effect exerted upon tooth 3; the subtraction and addition may be accomplished by adding the line 2-3, which is in phase with the vector *a* of Fig. 2 and = two-eighths of *a*, to the line 0—2. The resultant line 0-3 represents the magnetizing effect exerted upon tooth 3. In the same way the magnetizing effects exerted upon all 16 teeth may be easily determined. The square 16-4-8-12 is obtained in this way. If a uniform reluctance over all the poles is assumed, the vectors 0-1, 0-2, 0-3, etc., may at the same time be considered to represent the fluxes in the teeth 1 to 16.*

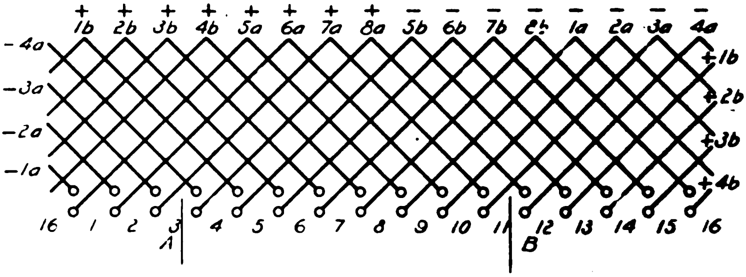

FIG. 1.—Space values of the rotating field.

2. *Diagram of the space values of the total field.* It is obvious that the vector representing the total field over a certain arc of the pole face may be easily obtained by simply adding the vectors of those teeth which form part of the arc under consideration. Thus in order to obtain the vector representing the total flux of an arc equal to a full pole pitch, the fluxes of 8 adjacent teeth have to be added. If, for instance, the fluxes of teeth 2 to 9 are added as shown in Fig. 3, we obtain the vector 6*a*, which represents the total flux over an arc comprising the teeth 2 to 9; that is, over an arc equal to the pole pitch. In order to find the total flux over the teeth 3 to 10, the complete addition does not need to be repeated; it is only necessary

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* This diagram for the tooth fluxes was evolved by Professor H. Görges, Dresden, and is published in *Electrotechnische Zeitschrift*, January 3, 1907.

to subtract from 6*a* the vector 2 and to add the vector 10; thus the desired vector, 7*a*, which represents the total flux over the teeth 3 to 10, is quickly obtained. In the same way we find:

Vector	8*a*	representing the total flux over the teeth	4	to	11
"	5*b*	" " " " " " "	5	"	12
"	6*b*	" " " " " " "	6	"	13

etc.

The vector for the flux between any two points *A* and *B* on the pole face, which are a full pole pitch apart and which do not coincide with the primary current centers, may be just as easily determined. Suppose, for instance, that the points *A* and *B* are respectively one-third and two-thirds of a tooth pitch away from the next current point. The vector for the flux between the two points may then be found by adding to the vectors of the teeth 3 to 10; that is, to the vector 7*a* a vector equal to two-thirds of the vector 11 and by subtracting a vector equal to two-thirds of the vector 3. Thus the vector *A B* is obtained, representing the flux between the points *A* and *B*. It will be readily seen from this that any line from the center of the diagram to one of the sides of the polygon 6*a*, 7*a*, 8*a*, 5*b*, etc., represents the flux of some arc equal to the pole pitch.

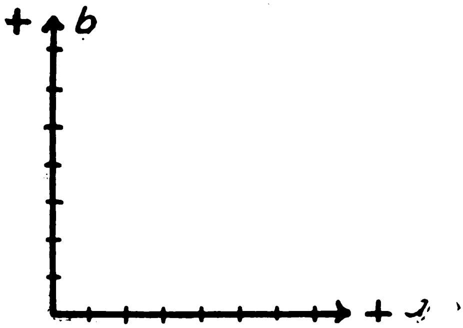

FIG. 2.—Space values of the rotating field.

3. *Diagram of potentials.* After the total flux over any full pitch area of the pole face is determined, the potential induced in a full pitch coil placed around this area may be represented by a vector proportional to and lagging 90 degrees behind the flux vector. If, for instance, the two sides of a secondary coil were placed on the points *A* and *B* the potentials induced in

the coil would be represented by a vector proportional to the vector *A B* lagging 90 degrees behind it. The potentials induced in the primary coils are represented by vectors proportional to and lagging 90 degrees behind the vectors 7*a*, 8*a*, 5*b*, 6*b*, etc. The potential vectors corresponding to the field vectors 7*a*, 8*a*, 5*b*, 6*b*, etc., are shown in Fig. 4, and correspond to the potentials induced in the coils 7*a*, 8*a*, 5*b*, 6*b*, etc., respectively. The total potential induced in the four coils of each group may be obtained by simply adding the four corresponding vectors, as shown in Fig. 4.

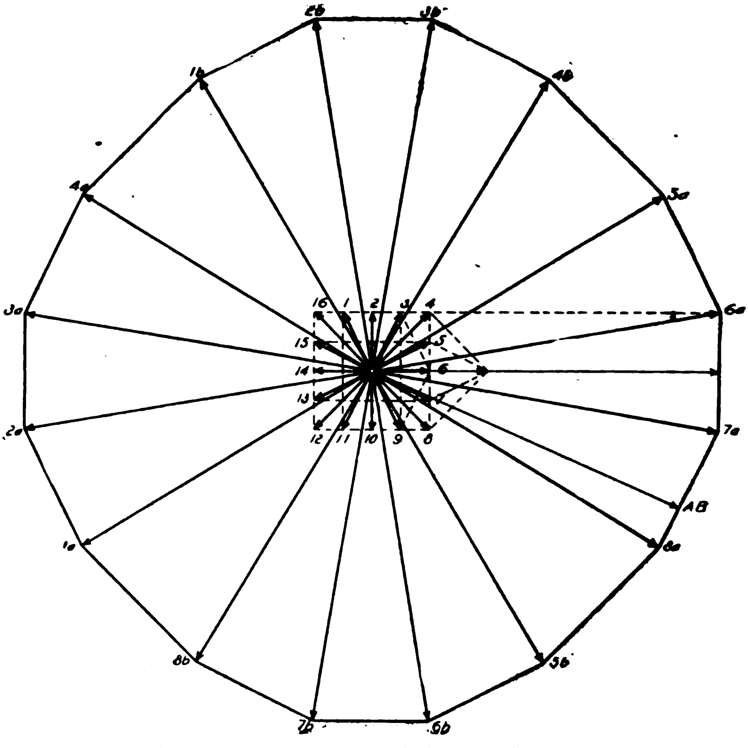

FIG. 3.—Space values of the rotating field.

4. *Diagram of the time values of the total field.* As has been stated, from Fig. 3 can be found the vectors, which represent the maximum values as well as the time-angle of the total fields over any full pitch area of the pole face. It was found, for example, that the vector *A B* represents the maximum flux value between the points *A* and *B* of Fig. 1. This flux does

not, however, necessarily represent the maximum flux which exists at the time at which the flux between A and B reaches its maximum value. It is obvious that there may be fluxes that find some path which does not go through the pole face area between A and B; or there may be fluxes that pass the pole face between A and B twice, and which therefore have no effect upon a coil located with its two sides at the points A and B. The question arises, therefore, what are the maximum values of the total field existing at any point of time? (In considering this question the leakage fluxes across the slots and the end connections of the coils may be neglected, since they can easily be considered separately.)

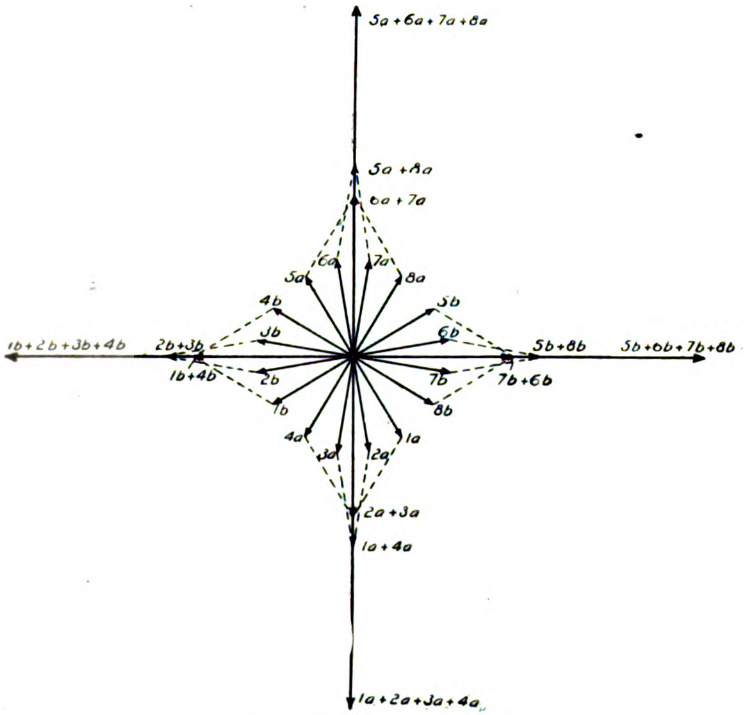

FIG. 4.—Potential diagram.

It was found that all the individual fluxes that go through each particular tooth are represented by the vectors 1 to 12 in Fig. 3. The maximum value of the flux at any time must therefore be represented by the sum of all individual fluxes that have the same direction at the time under consideration. If, therefore, in Fig. 5, which contains some of the vectors of Fig. 3, a time-line, *o m*, is assumed, the maximum field value for this time may be represented by the addition of all the projections of the individual teeth fluxes, which have the same direction, upon the time-line; or, what is equivalent, by the projection of the graphical sum of all the teeth flux vectors that are at one side of the perpendicular, *x y*, on the time-line. For the time-line under consideration the maximum field value is the graphical sum of the vectors 15, 16, and 1 to 6: The graphical sum of these vectors is represented by the vector *3b*, as before derived; consequently the value of the total field may be found by projecting the vector *5a* on the time-line. This holds for any time-line the perpendicular of which falls between the vectors 14 and 15, or between 6 and 7. In the same way the value of the total field for any time-line the perpendicular of

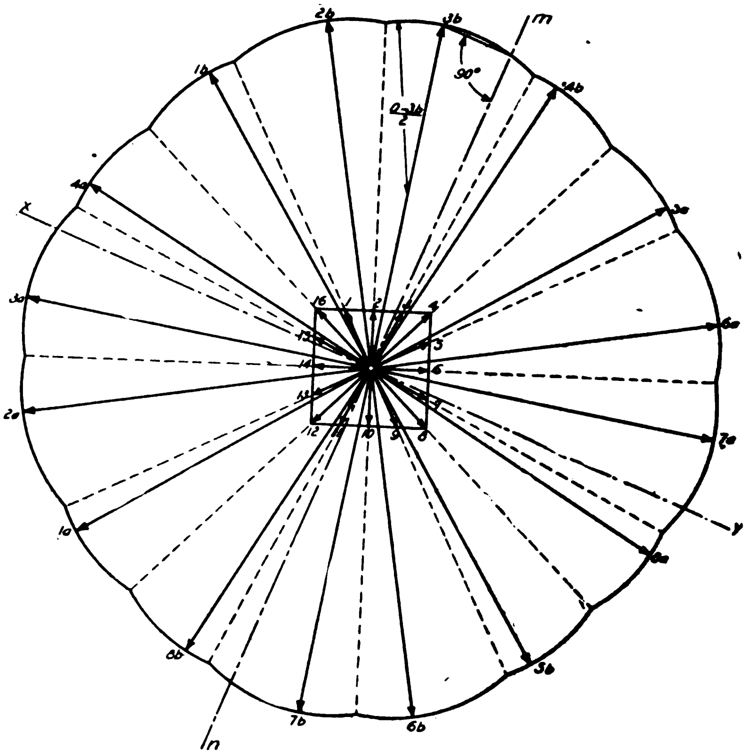

FIG. 5.—Time values of the rotating field.

which falls between the vectors 15 and 16 or between 7 and 8 may be found by projecting the vector 4*b* on the time-line, etc. It is also obvious that the locus of the projection points upon the time-line is a circle around the center of each vector. A very simple polar representation of the total field value in terms of the time-angle may therefore be obtained by simply drawing these circles for all the vectors, as shown in Fig. 5. The intersection of the various circles occurs when the perpendicular to the time-line passes the vectors of the teeth fluxes; therefore the time-angles of the intersection points follow directly from the time-angles of the teeth fluxes.

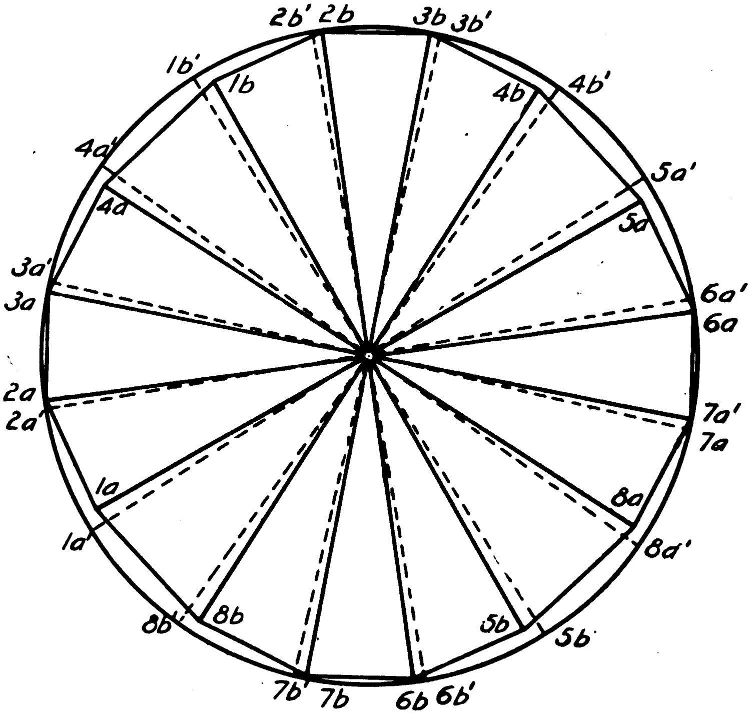

Fig. 6.—Comparison between the actual field and the equivalent sinusoidal field.

5. *Equivalent sinusoidal field.* After the vector representing the total potential which is induced in one group of coils has been found from Fig. 4 to equal E, it is possible to find the amplitude of the equivalent sinusoidal field; that is, the size of a field that has a sinusoidal space distribution rotates with

uniform speed and has the same effect as the actually existing field.

If n is the number of coils per pole, the angles between the potentials being induced in the coils is

$$\alpha = \frac{180}{n}$$

Moreover, if the potential induced in each coil is x, it follows from Fig. 7, for the case under consideration:

$$x = \frac{E}{2 \sin \frac{\alpha}{2} + 2 \sin \frac{3\alpha}{2}}$$

where $\alpha = 22° 30'$.

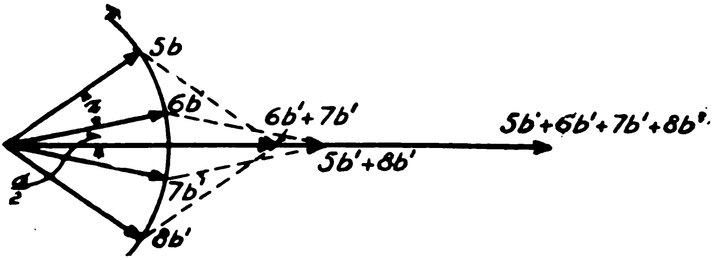

FIG. 7.—Diagram of the equivalent sinusoidal field.

In Fig. 6 a circle with a radius, x, is shown in combination with the diagram of Fig. 3. The dotted line vectors represent the potentials induced in the individual coils by the equivalent sinusoidal field, while the full-line vectors show the potentials induced by the actual field. In Fig. 8 the circle representing the equivalent sinusoidal field is shown in combination with the diagram on Fig. 5.

6. *Characteristics of the rotating field.* From the diagrams evolved so far, the main characteristics of the rotating field may be discerned merely by looking at the illustrations. It appears at once from Figs. 3 and 6, that the space values of the field vary in size; from Figs. 5 and 8 it appears that the total time values also vary in size. From the tooth diagram in Fig. 3, it follows that the maximum values of the individual teeth fluxes are different in size, and their time-angles differ

from the angles giving the space distances between the teeth; this means that the individual parts of the field rotate at non-uniform speed. That the total field rotates at non-uniform speed appears from Fig. 6, because the full-line vectors, that is, the vectors of the actual field values, would coincide with the dotted vectors, which indicate the time-angles of a uniformly rotating field, if the total field were to rotate at uniform speed. From Figs. 6 and 8 it also appears that the average of the space values, as well as the average of the time values, are smaller than the equivalent sinusoidal field values. Even the average of the flux vectors of the primary coils 5*a*, 6*a*, etc., is smaller than the equivalent sinusoidal flux value. It seems strange that the average of the primary field values induces the same resultant electromotive force as the equivalent but larger sinusoidal field. The reason for this follows however at once from Fig. 6, which shows that the actual field vectors 5*b*, 6*b*, 7*b*, and 8*b*, for instance, which belong to one group of coils, are less out of phase than are the equivalent vectors of the sinusoidal field 5*b*′, 6*b*′, 7*b*′, and 8*b*′. For this reason it happens that for some coil arrangements the actual field reaches at no time the value of the equivalent sinusoidal field.

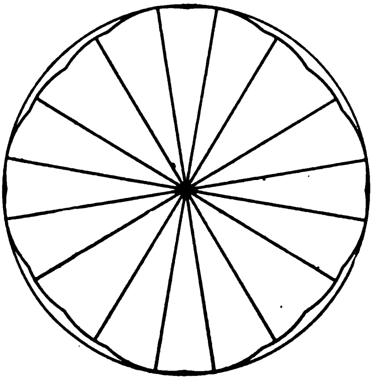

FIG. 8.—Diagram showing the time values of the primary and secondary fields and the leakage.

7. *Reactive effect of the secondary.* So far the diagrams have been evolved and the field treated without considering the reactive effects of the secondary. Assume now that a single coil, which may first be considered to be open-circuited, is rotated at synchronous speed round the pole face. Assume further

that the dotted lines $1a'$, $2a'$, $3a'$, etc., of Fig. 6 represent some time-positions of the rotating coil. They then give the positions of the secondary coil, in which its sides coincide with those of the primary coils $1a$, $2a$, $3a$, etc., respectively. For these positions the time vectors of the fields are represented by the full lines $1a$, $2a$, $3a$, etc., in Fig. 6, and the field inside of the moving coil, while the latter is in position $1a'$ may be found, for instance, by projecting line $1a'$ upon $1a'$, assuming that the sides of the rotating coil happen to coincide with those of the primary coil at the time represented by the coil $1a'$. For any other position of the coil the field inside the coil may be similarly found. It will be seen that the field as set up by the primary in the synchronously rotating secondary coil will fluctuate in size; therefore there will be potentials induced in the secondary coil, and if this coil is short-circuited reactive currents occur therein. It is also obvious that the more the polygon differs from a circle the larger these currents will be. The detailed treatment of the reactive currents takes considerable space and will be given later. It may be sufficient to state here that the currents in the secondary tend to keep up a field of sinusoidal space distribution and uniform size rotating with uniform speed. This field will naturally assume a value equal to an average of the field values originally induced by the primary. From Fig. 8 it follows that this average value will be smaller than the previously found value of the equivalent sinusoidal field. It follows, therefore, that the counter electromotive force induced by the field which is under the influence of the secondary reactance will be smaller than that induced by the original field. This, in turn, will cause a larger primary magnetization current in order to make up for the decrease caused by the secondary reaction. For this reason the magnetizing current of a motor with short-circuited and synchronously rotating secondary will be larger than the current of the motor with open secondary. The ratio of the two currents is the ratio of the average time values of the actual field as originally set up by the primary (open secondary assumed) and the value of the equivalent sinusoidal field. This ratio may be called the reactance factor.

8. *Derivation of coefficients.* The above diagrams lend themselves readily to the derivation of such factors as are required for the practical calculation of the rotating field and its magnetizing current. By drawing a segment of the diagram on

cross-section paper, as shown in Fig. 9, the problem of exactly determining the various factors is reduced to simple geometrical calculations, which may be quickly made with the aid of a table giving the squares and the square roots of figures and the angle functions. Various methods of proceeding and various factors may be chosen for the calculation of the magnetizing current and the field. It seems to the writer, however, that the relative merits of each coil arrangement may be best recognized if a coil arrangement with one slot per pole per phase is chosen as a base.

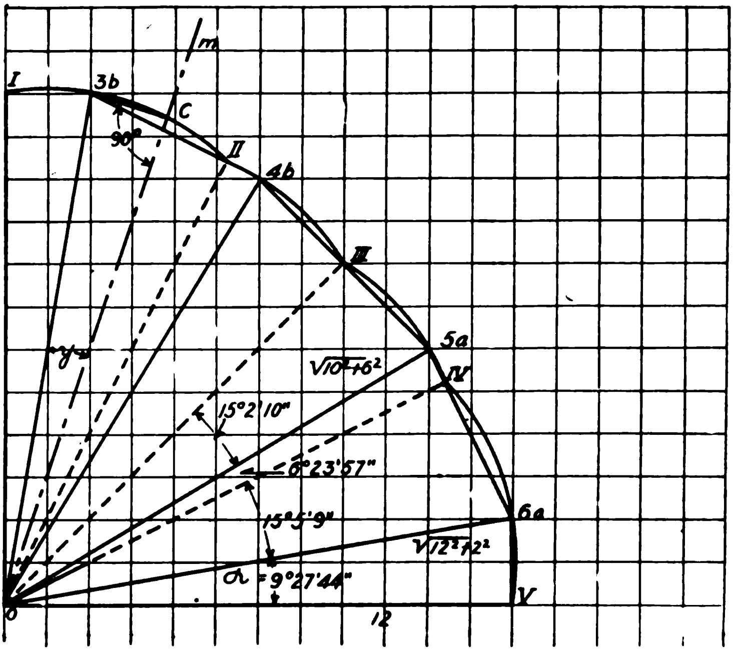

Fig. 9.

a. Potential factor. If, for instance, the potential being induced by a given sinusoidal field rotating with a given uniform speed is E_1, under the assumption of a given full-pitch winding located in one slot per pole per phase, the potential E_n induced by the same field in the same winding distributed over n slots per pole per phase may be

$$E_n = k_p E_1,$$

where k_p may be called the potential factor. The factor k_p is found from diagrams as shown in Fig. 7, and from the formulas given in connection therewith. The curves of Fig. 11 give the factor k_p for two-phase and three-phase full-pitch windings in terms of the total number of slots per pole.

b. Current factor. We assume further that a certain number of ampere-turns in a full-pitch winding wound in one slot per pole per phase induces, in case of an open-circuited secondary, a field, equivalent to the sinusoidal field F_1; and that the same number of ampere-turns in case of the same winding wound in n slots per pole per phase induces with an open-circuited secondary a field which is equivalent to a sinusoidal field F_n. The ratio of the two equivalent sinusoidal fields,

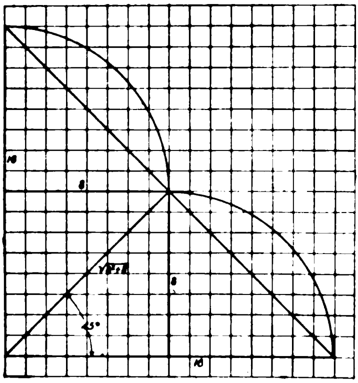

FIG. 10.—Diagrams for the determination of the various factors.

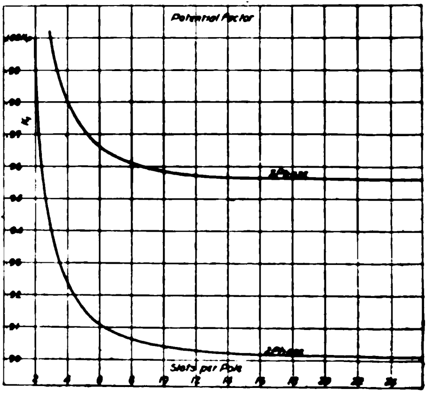

FIG. 11.—Potential factor.

$$k_c = \frac{F_n}{F_1}$$

may then be called the current factor.

The latter may be found by drawing, in addition to the diagram of Fig. 9, the diagram for one slot per pole per phase as shown in Fig. 10, the same number of total ampere-turns being assumed for both cases. The ratio of the equivalent sinusoidal fields found from the two diagrams is then the current factor k_c. The curves in Fig. 12 give the current factors for two-phase and three-phase full-pitch windings in terms of the total number of slots per pole.

c. Reactance factor. The potential and current factors are sufficient for calculating the magnetizing current with an open-circuited secondary. In order to find the exact magnetizing current for the case of a short-circuited synchronously rotating secondary the previously mentioned reactance factor has also to be determined. For this purpose we have to find the average value of the time values of the total field. From Fig. 9 it is seen that for any time-line, O_m, during the time period I–II the time value of the field is

$$O\,C = O\,3\,b \cos y.$$

The average value over one period may therefore be found by a very simple integration. Since the diagram in our case has, however, eight symmetrical segments, it is sufficient to find the average value for one of the eight segments. Thus we find the average time value of the field from segment III–IV–V to be:

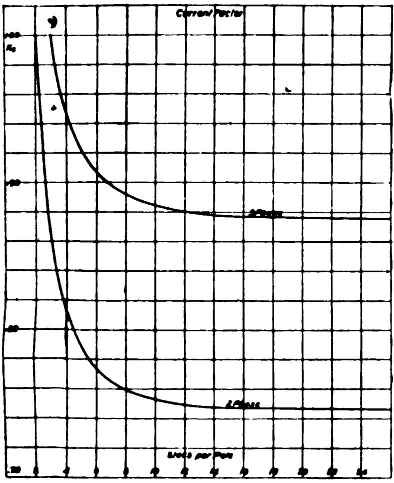

Fig. 12.—Current factor.

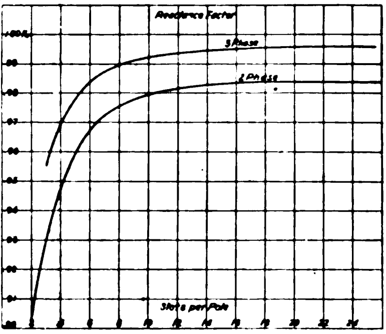

Fig. 13.—Reactance factor.

$$F_a = \frac{4}{\pi}\left[\sqrt{12^2+2^2}\int_{-9^\circ\,27'\,44''}^{15^\circ\,5'\,9''} \cos y \quad + \sqrt{10^2+6^2}\int_{-6^\circ\,23'\,57''}^{15^\circ\,2'\,10''} \cos y\right]$$

or

$$F_a = \frac{4}{\pi}\Big[\sqrt{12^2+2^2}\,(\sin 15^\circ\,5'\,9'' + \sin 9^\circ\,27'\,44'')$$
$$+ \sqrt{10^2+6^2}\,(\sin 15^\circ\,2'\,10'' + \sin 6^\circ\,23'\,57'')\Big]$$

The various angles may be best found from their tangent, which follows directly from the figure. For the first angle α we have for instance

$$\tan \alpha = \frac{2}{12} \text{ therefore}$$

$$\alpha = 9° 27' 44''$$

The reactance factor is found from

$$k_r = \frac{F_a}{F_n}$$

The curves in Fig. 13 give the reactance factor for two-phase and three-phase full-pitch windings in terms of the total number of slots per pole.

d. Magnetization factor. In practice the calculation of the magnetizing current for the running motor is of most interest. therefore the current factor and the reactance factor may be combined to one factor

$$k_m = k_r \, k_c,$$

which may be called the magnetization factor. The latter is given for two-phase and three-phase full-pitch windings by the curves of Fig. 14.

e. Resultant factor. In cases where the magnetizing current is found directly from the impressed voltage, all three of the factors, k_p, k_c, and k_r, may be combined as a resultant factor

$$k = k_p \, k_c \, k_r$$

The latter is given for two-phase and three-phase full-pitch windings by the curves of Fig. 15.

9. *Calculation of the field and its magnetizing current.* In practise the impressed potential is known as a rule, and the field and its magnetizing current are to be determined. If F_1 is the required sinusoidal field for the one slot per pole per phase arrangement, we find for other arrangements:

a. For open-circuited secondary:

The equivalent sinusoidal field $F_n = \dfrac{F_1}{k_p}$

The average of the time values of the actual total field

$$F_a = \frac{F_1}{k_p} k \times k_r$$

b. For short-circuited and synchronously rotating secondary: The equivalent sinusoidal as well as the actual field

$$F_n = \frac{F_1}{k_p}$$

If I_1 is the required magnetizing current for open-circuited secondary with the one slot per pole per phase arrangement, we find for other arrangements:

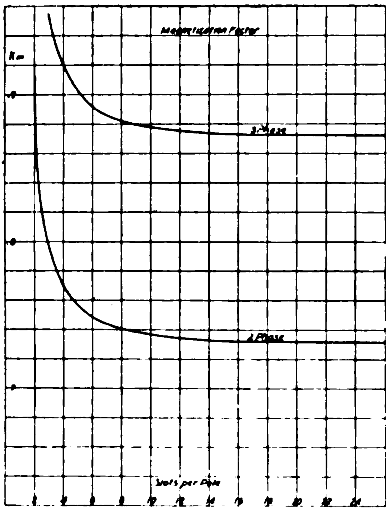

FIG. 14.—Magnetization factor.

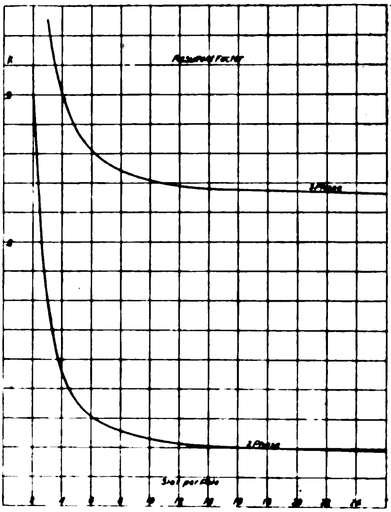

FIG. 15.—Resultant factor.

a. For open circuited secondary:

$$I_n = \frac{I_1}{k_p \times k_c}$$

b. For short-circuited synchronously rotating secondary

$$I_n = \frac{I_1}{k_p \times k_c \times k_r} = \frac{I_1}{k}$$

10. *Magnetic leakage.* The diagrams also give a means for deriving the magnetic leakage. The time values of the total fluxes in the secondary may be determined similarly to the time values of the primary flux, by finding the vectors for the fluxes in the secondary coils and drawing circles round their centres.

Let us assume, first, that the secondary has the same number of slots as the primary, and that the secondary is in a position in which the sides of the coil coincide with those of the primary. Then of course the secondary fluxes are always the same as the primary fluxes, and the potentials induced in the secondary are the same as in the primary, slot and end-connection leakage being neglected. Therefore the curve of Fig. 8 represents for this case the primary flux as well as the secondary flux; that is, the leakage flux is zero.

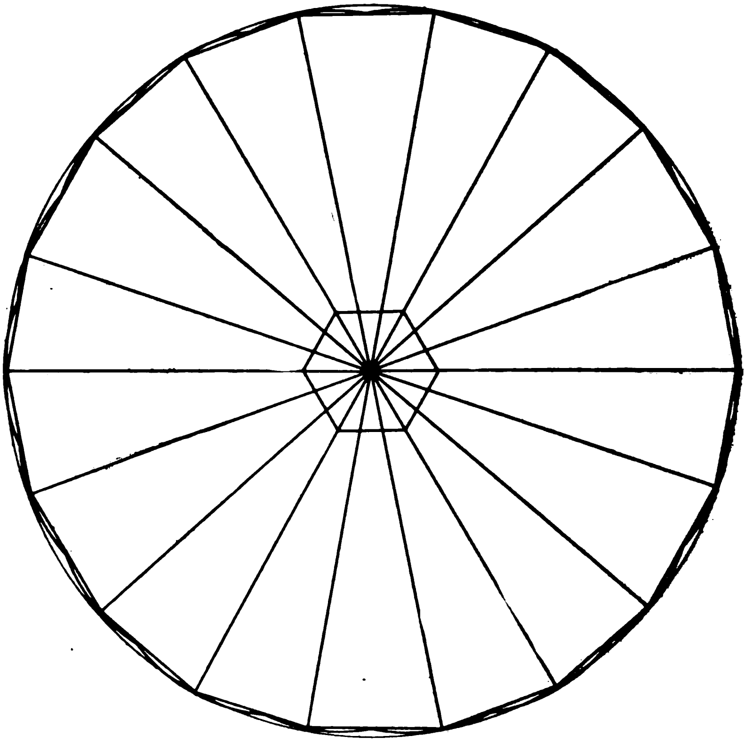

FIG. 16.—Field diagrams for a three-phase motor with three slots per pole per phase.

The rotor may now be shifted so that the sides of its coil are located in the middle between the coil sides of the primary. The field vectors of the secondary are then represented by the dotted lines of Fig. 17, which go from the center of the diagram to the middle points of sides of the polygon. By drawing the circle segments around the centers of these dotted lines, we obtain the inner curve shown, Fig. 17, which represents the time values of the total secondary flux. The difference between the outer and the inner curve represents the leakage flux for the rotor position under consideration.

In Fig. 18 the same curves are shown for a secondary position between that of Figs. 8 and 17. The three figures show clearly the change of the leakage field with the secondary position.

In Fig. 19 the curves for the fluxes are shown for a rotor in a position like that of Fig. 17, the number of secondary slots being reduced to half their former number. A comparison with Fig. 17 shows at once how the leakage has increased by the reduction of the secondary slots.

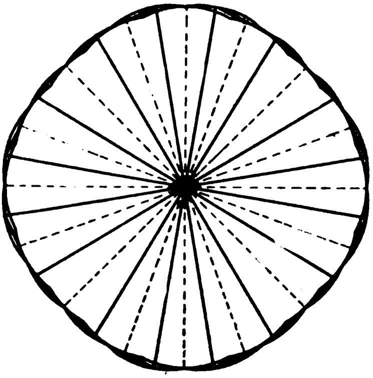

FIG. 17.—Diagram showing the time values of the primary and secondary fields and the leakage.

Instead of determining the leakage fluxes as the difference between the primary and secondary fluxes, the zig-zag and belt leakage fluxes may be also determined directly from the diagram of the teeth fluxes. The slot leakage may also be determined by the latter.

11. *Comparison between two-phase and three-phase fields.* It may be well to give for the purpose of comparison, a diagram for a three-phase winding. Fig. 16 shows the diagram for the teeth fluxes, the space values, and the time values of the total

fluxes of a motor with three slots per pole per phase; that is, approximately the same number of slots per pole as for the two-phase case considered before—nine slots per pole instead of eight. It appears at once from the diagram that the three-phase field approaches the ideal condition much more than does the equivalent two-phase field. All three diagrams given in Fig. 16 give curves that much more approximate a circle than the curves for the two-phase field. The superiority of the three-phase field also appears from the curves of Figs. 11 to 15.

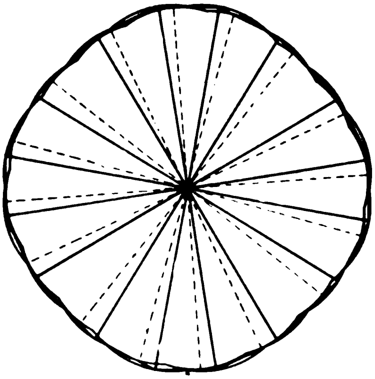

Fig. 18—Diagram showing the time values of the primary and secondary fields and the leakage.

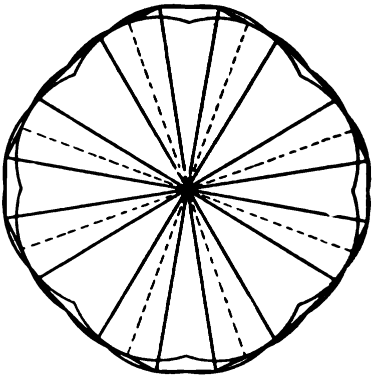

Fig. 19—Diagram showing the time values of the primary and secondary fields and the leakage.

It is well known that the two-phase field requires more magnetizing volt-amperes than the equivalent three-phase field. It may also be shown that the leakage of the two-phase field is larger than that of the three-phase field. These facts are considered by every designer, and result in the well known differences of 0.5 to 3 per cent. in the calculated values of the efficiency and power-factor, or possibly in some difference in the starting torque and pull-out torque of the two motor types, if they are designed for equal power-factor.

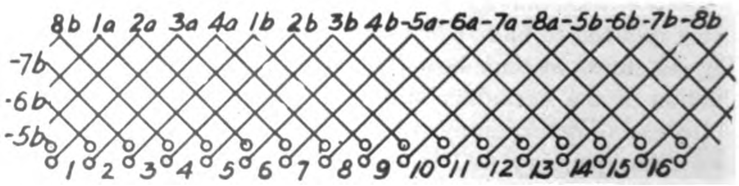

Fig. 20.

The comparison of the above diagrams shows, moreover, that a two-phase motor will have larger reactive currents in the secondary. The comparison of the reactance factors shows that the amplitude of the higher harmonics in the primary is larger in the two-phase motor than in the three-phase motor. Consequently both of the latter phenomena tend to reduce the efficiency of the two-phase motor more than that of the three-phase motor;

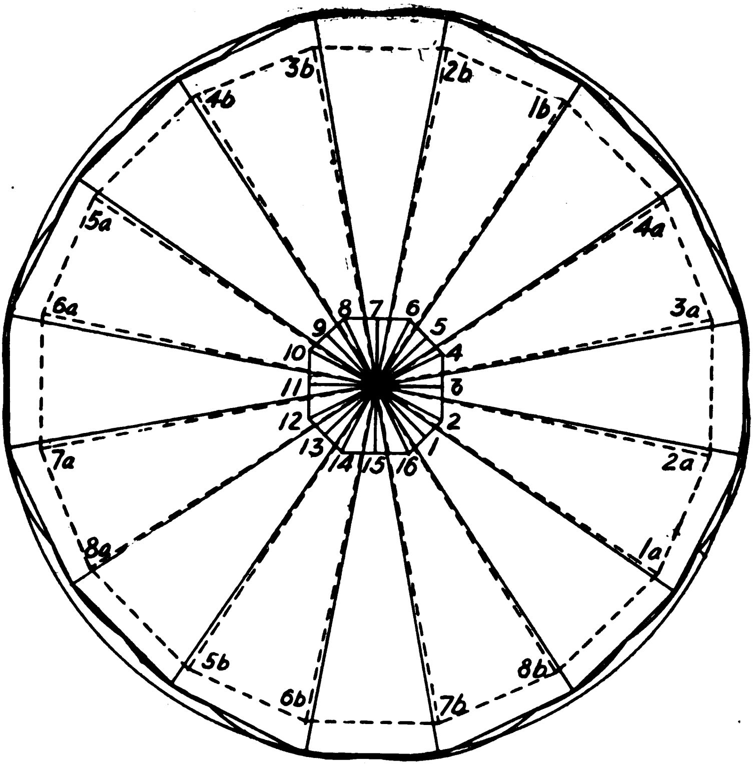

FIG. 21.—Field diagram for a two-phase motor with four slots per pole per phase and a coil-throw 1 to 7.

12. *Fractional pitch.* The diagrams may also be applied to fractional pitch windings. Fig. 20 shows a two-phase winding with four slots per pole per phase and 75 per cent. pitch. Fig. 21 gives the diagram for this winding. The inner small polygon gives the individual teeth fluxes; the outer polygon gives the space values of the field; the curve consisting of segments of circles gives the time values of the total field. These three

figures are derived in the same manner as that previously shown for full-pitch windings. Since in the case of fractional pitch windings the fluxes interlinking with the primary coils are smaller than the total primary fluxes, it is necessary to find the time

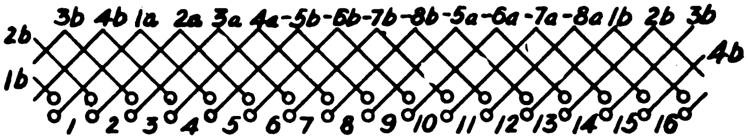

Fig. 22.—Field diagram for a two-phase motor with four slots per pole per phase and a coil-throw 1 to 5.

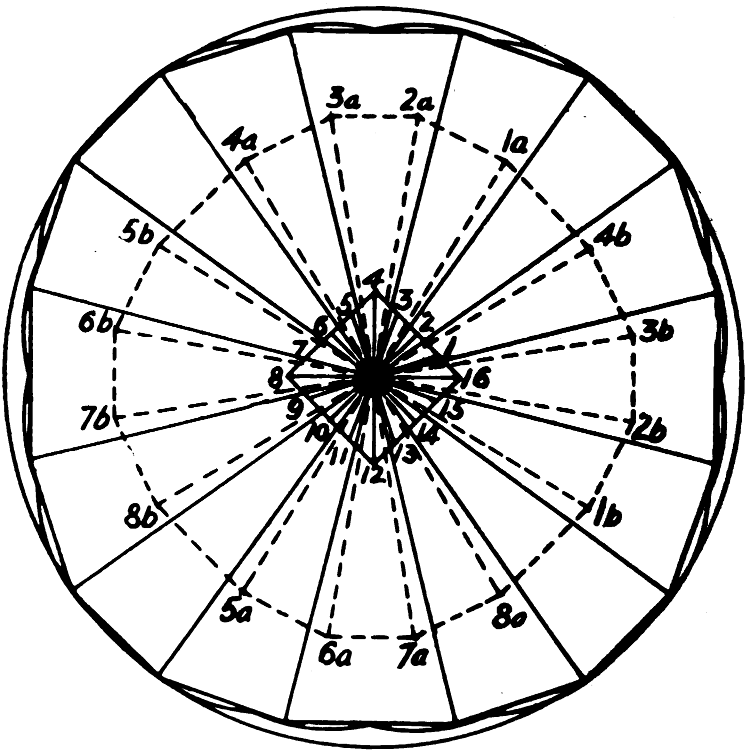

Fig. 23.

values of the fluxes interlinking with the primary coils in order to find the potentials induced in the primary coils. These fluxes are found for each coil by adding the fluxes of the teeth, surrounded by the coil under consideration. The primary coil fluxes thus obtained are shown in Fig. 21 by the vectors 1*a*, 2*a*, etc., which corresponds to the coils 1*a*, 2*a*, etc., of Fig. 20 respectively. The various factors may be derived in the same way as before for the full-pitch windings. The equivalent sine field is represented in Fig. 21 by the circle.

Figs. 22 and 23 give the same slot arrangement as before with a two-phase 50 per cent. pitch winding.

In Fig. 24 the diagrams for the space values of the field for all pitches for two phase 8 slots per pole between 0 per cent. and 100 per cent. are shown. The numbers given indicate the throw of the coils, for which the various polygons apply. It appears that the full-pitch polygon throw 1 to 9 is flattened in a direction 45 degrees to the horizontal and vertical. The same applies to a smaller extent for the 87.5 per cent. pitch —throw 1 to 8— and the 75 per cent. pitch—throw 1 to 7— windings. For the 62.5 per cent. pitch—throw 1 to 6— winding the polygon is closest to a circle. The circle is shown here only for comparison. If the pitch is reduced further, the polygons

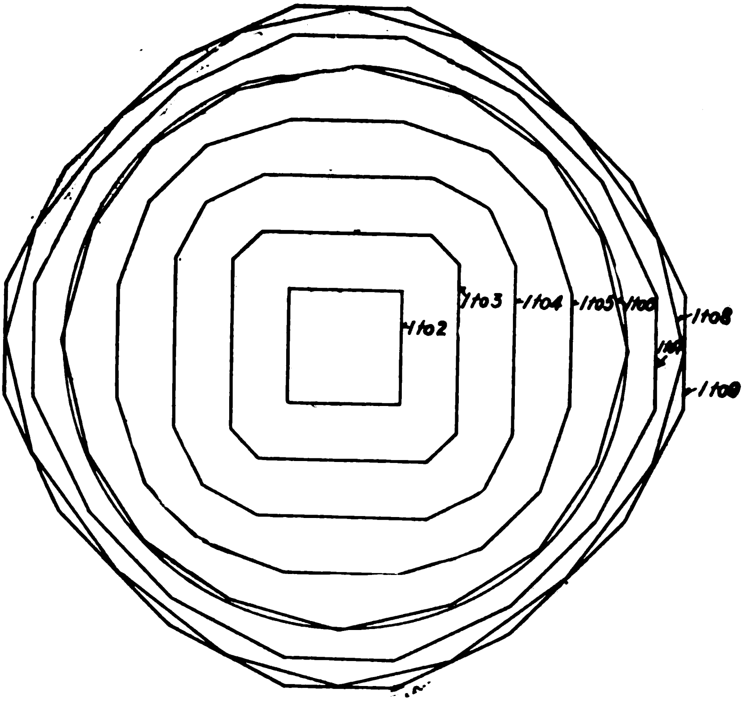

FIG. 24.—Diagram showing the space values of the rotating field for various pitches.

become flattened in the vertical and horizontal direction and the flattening becomes the larger the more the pitch is reduced. This means that by reducing the coil pitch from full pitch, the field may be improved to a certain point; it will, however, become worse again if the pitch is reduced below a certain amount. Without delving further, it may be safely concluded that for the 75 and 62.5 per cent. pitches the secondary reactive currents and the higher harmonics in the primary are the smallest. It may be also shown that the leakage coefficient for this pitch is reduced. The 75 and 62.5 per cent. pitches are therefore advantageous in various respects for a two-phase winding and 8 slots per pole. For most windings it will be found that the best field is obtained when the phases overlap one-half to one-third. If the phases overlap entirely, the field conditions are not any better than for full pitch.

13. *Dead points.* It is well known that the starting torque of induction motors varies with the rotor position. This variation is due to the variation of the leakage with the rotor position. Since the diagrams shown in Figs. 8, 17, 18, and 19 give a means for studying the variation of the leakage with the rotor position, etc., they also give a means for studying the question of the varying starting torque.

14. *Noise in induction motors.* Although little can be said with any degree of certainty about motors running noisily, it is almost certain that the reactive currents in the secondary and the higher harmonics in the primary are two of the many fundamental causes of noise. Therefore the chances for noise can be reduced by keeping the amplitude of these currents as low as possible. In this respect the above diagrams show that three-phase motors are less likely to be noisy than two-phase motors with a corresponding pitch and number of slots. From Fig. 24 it follows that the chances for noisy operation may be greatly reduced by choosing the proper pitch; in the case under consideration the pitches are 75 and 62.5 per cent.

While it has not been possible to treat in this paper the various topics much in detail it will be readily seen that the graphical method before outlined will answer a great many questions. Moreover, the graphical treatment always has the advantage of giving a clearer conception of the physical facts than analytical formulas. The analytical treatment is rather complicated and requires in many cases too much time.

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APPLICATION OF STORAGE BATTERIES TO REGULATION OF ALTERNATING-CURRENT SYSTEMS

BY J. L. WOODBRIDGE

The general function of a storage battery in connection with an alternating-current system is the same as in a direct-current system, namely, to relieve the power plant and in some cases the transmission lines of the fluctuations of load, permitting the generating machinery and conductors to be utilized to the greatest advantage and at maximum economy by subjecting them to a steady load equal to the average, instead of a load whose fluctuations in some instances, as in heavy interurban railway work and in many industrial plants, are exceedingly rapid and severe. In many cases where alternating currents are developed, the advantages of a regulating storage battery are even more pronounced than in direct-current service, for the following reasons:

1. Alternating-current generation is particularly applicable to long distance interurban railway work where steam railroad conditions prevail, involving heavy units operating at comparatively infrequent intervals, producing fluctuations of load abnormally high as compared with the average. These conditions are comparable, except on a largely magnified scale, with those obtaining on the four or five car electric roads so common in the early history of electric railways.

2. In many cases alternating current is developed at water-power plants and transmitted for considerable distances, and it is well known that a storage battery affords special advantages in connection with the operation of a water-power supply to which are added the advantages of a practically constant current on the transmission lines.

3. In many such cases of water-power development with alternating-current transmission, power is sold on the maximum demand basis, and the saving in power bills effected by removing the peaks and fluctuations with a storage battery makes the battery installation a very attractive investment.

4. The auxiliary apparatus required in connection with a storage battery adapted for regulating an alternating-current system may also be used for changing the frequency or controlling the power factor.

5. The increasing use of gas engines in steel plants for utilizing the furnace gas offers a large field for the application of storage batteries, and in most of these plants the heavy loads and the large area covered call for alternating-current generation and distribution.

The conditions to be met in the various alternating-current systems include a number of different combinations which may be classified broadly as follows:

A. GENERATION ENTIRELY ALTERNATING-CURRENT

I. Load wholly direct-current. Distribution by alternating-current transmission lines to direct-current sub-stations.

II. Load wholly alternating-current, polyphase.

III. Load wholly alternating-current, single-phase.

B. GENERATION AND LOAD PARTLY ALTERNATING-CURRENT AND PARTLY DIRECT-CURRENT

IV. Direct-current fluctuations preponderating.

V. Alternating-current fluctuations preponderating.

Below is given an outline of the methods which have been adopted or suggested for handling each of these cases. In every case it is of course necessary to have converting apparatus for interchangeably transforming alternating and direct currents as well as automatic apparatus for controlling the transfer of energy between the alternating- and the direct-current circuits. Such apparatus is taken up in detail in the latter part of this paper.

I. Under this heading are included systems in which alternating current is generated and transmitted to direct-current sub-stations for supplying a direct-current fluctuating load such as that of the ordinary interurban direct-current trolley system. The early applications of storage batteries to systems of this kind involved the installation of a battery at each of the several sub-stations to regulate the fluctuations of direct-current load at that point. This required nothing more than the ordinary direct-current controlling apparatus. In some recent installations, however, the conditions have been such that it has been found advantageous to concentrate the battery capacity at one point, a single battery being installed arranged to control the total combined fluctuations of load on the entire system. Such an arrangement obviously reduces the first cost for two reasons. First, the total battery capacity required will usually be considerably smaller where the battery is concentrated in this way, inasmuch as the maximum fluctuations of the combined load will ordinarily be less than the sum of the maximum fluctuations occurring at the several sub-stations, since the latter do not occur simultaneously. Second, the cost per unit of capacity of a single large battery will obviously be less than that of a number of smaller installations. This is particularly true of the auxiliary apparatus.

In order to permit of this concentration of the battery capacity it is necessary to select some point for installing the battery, from which the conductors carrying the total output of the generating plant are readily accessible. In many cases a converter station located at the power house itself affords the most suitable location. In other cases where the transmission is wholly in one direction from the power house the nearest sub-station may be selected. In such cases the battery with its regulating booster is connected to the direct-current sub-station bus-bars in the usual manner, but the booster is controlled by means responsive to the total alternating-current output of the generating plant. Its control is accomplished by means of current transformers located in the main alternating-current bus-bars or transmission lines, between the converter station and the generators, whose secondaries will furnish alternating-current to the battery controlling apparatus proportional to the total output of the power station. In some cases current transformers are located in the individual generator circuits, their secondaries being connected in parallel to give a combined output proportional to the total generator load.

By this arrangement the same converters which are required for supplying the local direct-current load on the sub-station are also used for transforming the battery current, and in many cases no greater converter capacity is called for on account of this latter function. For example, the total load on the system may vary from 500 to 3000 kw. with an average of 1500 kw. The direct-current demand on the sub-station where the battery is located may vary from zero to 1500 kw. Converting apparatus must therefore be installed at this sub-station of sufficient capacity to handle a momentary load of 1500 kw. It is evident that with the battery regulating on the total load this converting apparatus will never have to deliver more than 1500 kw. to the sub-station, since this is the total output from the generators and this amount of energy will be supplied to this sub-station only at rare intervals when the total load on the rest of the system is zero. Nor will this converting apparatus be called upon to transmit energy in the reverse direction to a greater amount than 1500 kw. since the total maximum load on the entire system is 3000 kw. of which the main generator is always supplying 1500. At times of maximum total load there will

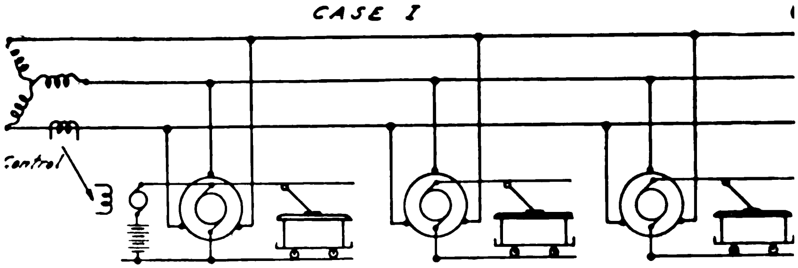

FIG. 1

usually be a direct-current load of considerable magnitude on the regulating sub-station which must first be taken up by the battery before the latter can invert the converters and feed back into the alternating-current mains, thus reducing to that extent the amount of energy inverted. The general operation of the battery in this scheme is to relieve the sub-station of more or less of its direct-current load at times of increased load on the rest of the system, thus preserving a constant load on the generating units. It being necessary on account of the direct-current load to maintain constant voltage on the direct-current bus-bars, a battery booster will be required to cause the battery to charge and discharge, this booster being controlled from the alternating-current circuit. This case is illustrated diagrammatically in Fig. 1.

II. In this case the current is generated and utilized as polyphase alternating current, there being no direct-current circuit. Under these conditions the battery would be located either at the main generating station or in some cases at the center of load, and inasmuch as the entire output of the battery must be converted into alternating current, converting apparatus, either motor-generator sets or synchronous converters, must be provided of sufficient capacity to handle the maximum battery discharge. If a motor-generator set is used for control, the charge and discharge of the battery may be accomplished by varying the voltage of the direct-current machine in response to fluctuations of the alternating-current load. Synchronous converters are undoubtedly preferable for this purpose, particularly if the fluctuations of load are extremely rapid. If a motor-generator is called upon to transfer energy from the battery to the alternating-current circuit it will deliver energy to the latter circuit only after its armature has been driven somewhat ahead of its normal phase position, and owing to the inertia of the armature some appreciable time must elapse after the battery has begun to discharge into the direct-current machine before the alternating-current machine is delivering the equivalent energy to the alternating-current circuit and a time lag is thus introduced. With a synchronous converter this effect is practically eliminated.

With the latter type of machine, however, special means must be provided for varying the direct-current voltage at the battery terminals to compel the battery to charge and discharge. If a standard converter is employed a battery booster will be required to produce this voltage variation. This booster will be provided with field control responsive to the fluctuations of alternating-current load, such controlling apparatus being described below.

On account of the absence of direct-current load, however, a constant direct-current voltage is not required, and in order to dispense with the battery booster a synchronous converter providing for a variable ratio between the alternating- and direct-current voltages has been developed. This machine has been designated the " split-pole " converter owing to the fact that the control of the transformation ratio is brought about by dividing each pole into two or more sections whose excitations are separately controlled. By this means the direct-current voltage of the converter is varied to cause the battery to charge and discharge while the alternating-current voltage is maintained practically constant. This type of machine offers very considerable advantages in the way of simplification and increased efficiency of operation over apparatus involving boosters or motor-generator sets. It is found to be particularly adapted for handling extremely rapid fluctuations of alternating-current load. It must be borne in mind that in dispensing with the booster the means for maintaining a constant-potential direct-current bus-bar is eliminated and any circuit connected directly to the battery terminals will be subject to more or less variation of voltage due to the charge and discharge of the battery. This case is illustrated in Fig. 2.

III. In this case power is generated as alternating current and is supplied to a single-phase circuit. One of the most noted examples of this class of installation is found at the frequency-changing station of the Spokane & Inland Ry. Co. at Spokane, Washington. The equipment of this station includes four frequency- and phase-changing motor-generator sets, each set consisting of three direct connected machines, viz., a 60-cycle, 3-phase induction motor of 1000 h.p. capacity, receiving power from the incoming transmission line; a 1000-kw., single-phase, 25-cycle, 2200-volt generator, delivering current to the railroad; and a 750-h.p., 500-volt, direct-current machine, which is connected to the battery and acts as a generator or a motor when the battery is respectively charging or discharging. The battery consists of 275 cells having a capacity of 1920 amperes at the one-hour rate, and is provided with two motor driven boosters which may be operated in parallel. The boosters are controlled by apparatus which responds to the current in the incoming 60-cycle transmission line in such a way that small variations of this current vary the booster voltage, thus causing the battery to charge from or discharge into the direct-current

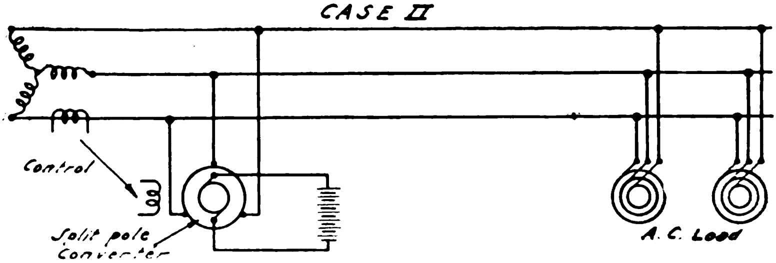

Fig. 2

machine to absorb the fluctuations of load on the single-phase circuit. This is one of the cases in which the financial results from a battery installation may be very clearly demonstrated, inasmuch as the power for the operation of the railway system is purchased on the maximum demand basis, and it is estimated that the reduction in the power bills effected by the battery in relieving the transmission line of load fluctuations will be sufficient to repay the initial investment in about three years. This application is illustrated in Fig. 3.

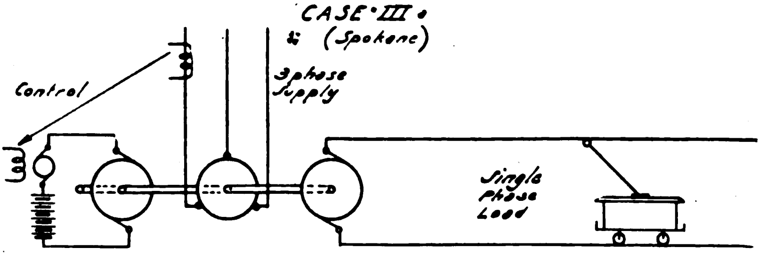

FIG. 3

Instead of the scheme above described it will be quite practicable to utilize the split-pole converter operating as a single-phase machine connected to the single-phase circuit with suitable transformers. The output of the battery will then be delivered to the railway circuit without the intervention of mechanical transmission, and the efficiency on discharge and therefore the net alternating-current output for a given battery discharge will be greater. This is illustrated in Fig. 4.

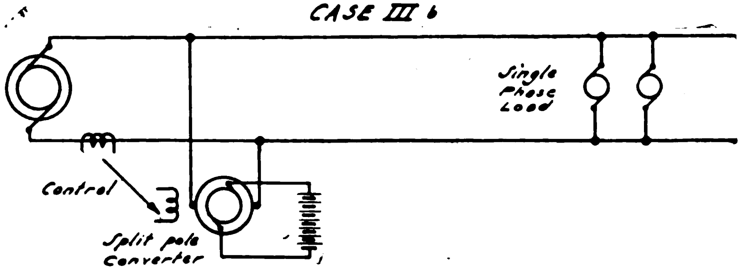

FIG. 4

IV. This and the following case include systems in which both alternating-current and direct-current generators are operated to supply a load which is partly alternating- and partly direct-current, the two circuits being interconnected by suitable converting apparatus. In case IV, the fluctuations of the direct-current load preponderate, and inasmuch as the direct-current bus-bar must ordinarily be maintained at constant voltage a battery booster is required, sufficient at least for the direct-current fluctuations. Since these latter constitute the greater part of the total load fluctuations, the booster should be made of sufficient capacity for the total battery output. The booster control would not differ in any way from the standard direct-current controlling apparatus. In order to transmit the fluctuations originating on the alternating-current circuit to the direct-current bus-bar special automatic control of the converting apparatus must be provided. The split-pole converter would undoubtedly be a most satisfactory method of providing this control, and inasmuch as the direct-current bus-bar voltage is practically constant only a very small change in ratio of conversion would be necessary, just sufficient to overcome the internal drop in the converter and static transformers.

Another method of providing for this automatic control of the converting apparatus consists in mounting on the shaft of the converter an alternating-current booster whose windings are connected in series between the alternating-current terminals of the converter armature and the collector rings. The field of this booster is controlled automatically in response to fluctuations of load on the alternating-current circuit, thus adding to or subtracting from the alternating-current voltage of the converter and thereby causing it to transmit energy in either direction between the alternating- and direct-current circuits as may be required to maintain constant load on the alternating-current generators. This latter arrangement is illustrated in Fig. 5.

V. The conditions included in this case are the same as in case IV except that the alternating-current load fluctuations preponderate. Inasmuch as the direct-current bus-bar voltage must be maintained constant a battery booster is required of sufficient capacity to handle the fluctuations of direct-current load. These fluctuations being comparatively small this booster capacity may be reduced to a minimum provided the fluctuations of alternating-current load are transmitted directly to the battery terminals instead of to the direct-current bus-bars. This latter may be accomplished by means of the split-pole converter which in this case is connected between the alternating-current circuit and the battery terminals, and is so controlled as to transmit directly to the battery the fluctuations of load originating on the alternating-current circuit. This is the scheme which has been adopted for controlling the load fluctuations at the electric power plant of the Indiana Steel Company, at Gary, Indiana.

For this plant there is being installed a battery consisting of two series of cells arranged to operate in parallel, each series consisting of 125 cells having a one-hour capacity of 4320 amperes. Provision has been made for the future extension of this plant by the addition of two more series of cells of the same capacity. Two direct-current boosters are provided, having sufficient capacity to handle the fluctuations of direct-current load, which will be only a small part of the total load fluctuations. For handling the fluctuations of alternating-current load a split-pole converter of 2000 kw. capacity is being installed, designed to provide a range of direct-current voltage from a minimum of 200 to a maximum of 300 volts with constant alternating-current voltage. The regulating field of this converter will be controlled by a special alternating-direct-current exciter, designed as described hereinbelow. Provision has been made for a second converter of the same design and capacity. This case is illustrated in Fig. 6.

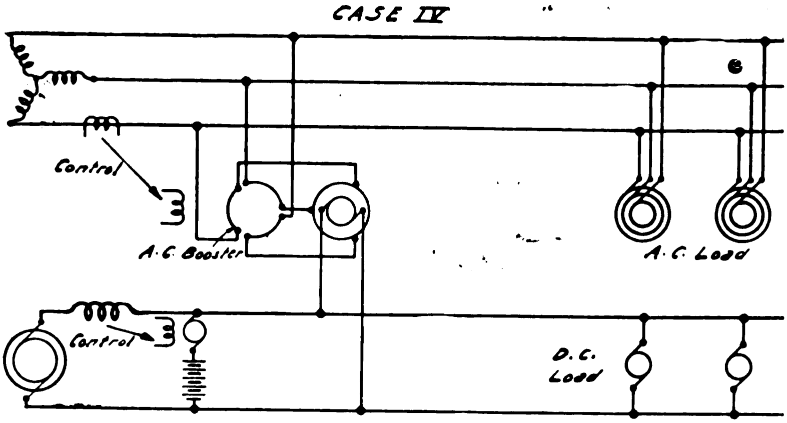

FIG. 5

Auxiliary apparatus. Under this heading are described three pieces of auxiliary apparatus which have been developed for controlling the operation of a battery in connection with an alternating-current circuit.

The first of these devices, the carbon regulator, calls for only passing notice, as its general design and operation are well known in connection with direct-current regulating plants. It is shown diagrammatically in Fig. 7, in which *x* and *y* are two piles of carbon discs subjected to variable pressure by means of the lever, *L*, which is pivoted between the two piles in such a way that any motion of this lever will increase the pressure on one pile and decrease that on the other. At one end of the lever is an adjustable spring, *T*, while from the other end is suspended the iron core of a solenoid, *S*, which carries the current to be regulated, or a current proportional thereto. The two carbon piles are electrically connected in series across the battery, *B*, while the field coil, *F*, which is to be controlled, is connected between a point in the circuit between the two carbon piles and the middle point of the battery. The variation of resistance in the two piles due to change of pressure causes a flow of current in one direction or the other through the field coil, *F*, which is therefore made responsive to the current in the solenoid, *S*. The application of the regulator to alternating-current control involves the substitution of an alternating-current solenoid for the usual direct-current coil. In those installations where the power factor is normally maintained approximately at unity, such as the usual alternating-current

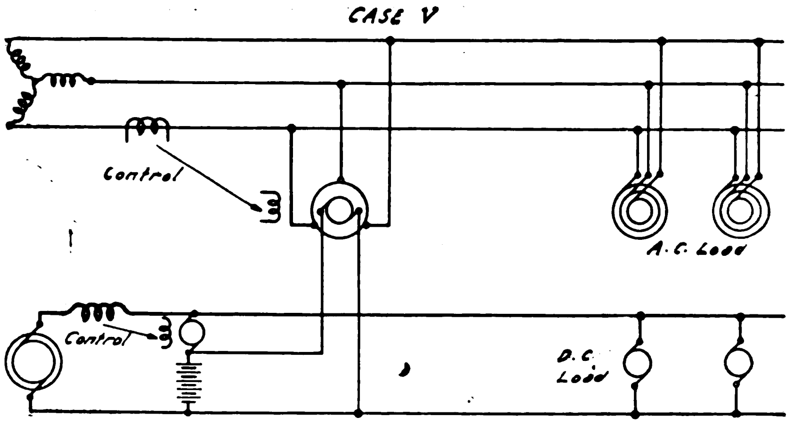

Fig. 6

generating plant supplying current to converter sub-stations for direct-current railway service, a single coil supplied with alternating current proportional to the current output of the alternators will give entirely satisfactory results, this current being practically proportional to the true watt output of the machines. If, however, the power factor is normally considerably less than unity or if it is subject to wide variations, it may be necessary to control the carbon regulator by means responsive to the energy component of the current and two coils may be used, one of which will produce a constant magnetic flux, while the other carries current which is in phase with the flux at unity power-factor, or whose energy component is in phase with the flux at power-factors other than unity.

The second piece of regulating apparatus which has been developed for this class of service is the split-pole converter.

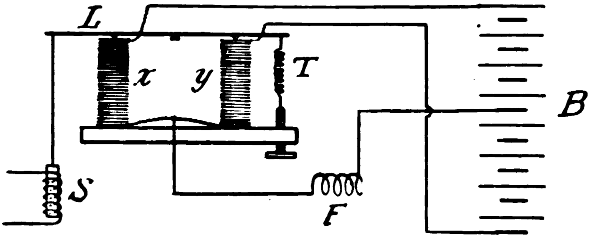

FIG. 7

This machine has already been mentioned in a recent paper before this Institute, but I wish to take up somewhat more in detail certain points in reference to the theory of its operation and the detail of its design.

As originally suggested this type of machine was constructed with each pole sub-divided into three parallel sections with suitable windings for varying the relative excitation of the three sections, the object being to secure a variation of direct-current voltage while maintaining a constant alternating-current voltage. The theory upon which this design was based may be illustrated by reference to Fig. 8, in which is shown an assumed distribution of field flux around the periphery of the armature. The line, *A B*, represents the developed armature periphery, the direct current brushes being located at *A* and *D*. The lines *a*, *b*, and *c*, represent the field strength of the three sections of one pole and the lines *d*, *e*, and *f*, that of the other pole under normal conditions of excitation. The result of this excitation will be a certain ratio between alternating- and direct-current voltage. If, now, the excitation of the outer pole sections *a*, *c*, *d*, and *f*, be increased, and that of the middle sections *b*, and *e*, be decreased, the field distribution may then be represented as the resultant of the auxiliary field *g*, *h*, *i*, *j*, *k*, and *l*, superposed upon the normal field. If, now, we consider the electromotive force developed in a section of the armature between the points *P*, and *Q*, which may be taken to represent two of the three phase taps located 120° apart, it will be seen that the auxiliary field will have absolutely no effect on the voltage in this section at any point in the revolution; for the sum of the shaded areas *x*, and *z*, is always equal and opposite to the shaded area *y*. The auxiliary field therefore interposes into the armature section between the points *P*, and *Q*, equal and opposite amounts of field flux, which exactly neutralize each other in the generation of electromotive force between *P*, and *Q*. The effect however of the auxiliary field on the direct-current voltage between the points of brush contact *A*, and *D*, is to produce an increase in that voltage for the reason that between these two points there are two areas of positive flux and only one area of negative flux due to the auxiliary field. Theoretically, therefore, this auxiliary field would produce an increase or decrease in the direct-current voltage without any effect whatever on the magnitude or wave shape of the alternating voltage, between the points *P*, and *Q*, provided these points are spaced 120° apart.

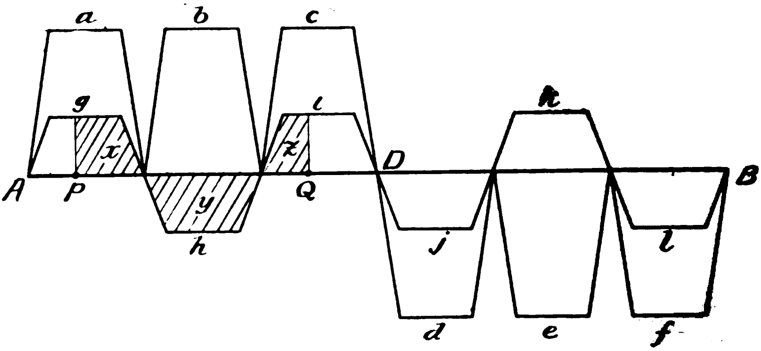

FIG. 8

Practically, however, it is necessary to allow a neutral area of zero field strength at the points A, and D, for commutation. This modification produces some disturbance of the wave shape of the alternating counter electromotive force, which, however, is not sufficient to interfere with the practical operation of the machine. In Figs. 9 to 14 inclusive, are shown oscillograph records giving the distribution of field flux obtained by an exploring coil and the corresponding wave shape of alternating electromotive force across two of the three phase collector rings, taken from a 500 kw. split-pole converter of this type. Fig. 9 shows the normal field distribution with all three sections of the pole equally excited and Fig. 10 is the corresponding wave shape of electromotive force; direct-current voltage 250. Fig. 11 shows the field distribution with the outer sections increased and the middle section reduced in excitation, while Fig. 12 shows the corresponding wave shape of electromotive force; direct-current voltage 280. Fig. 13 shows the field distribution

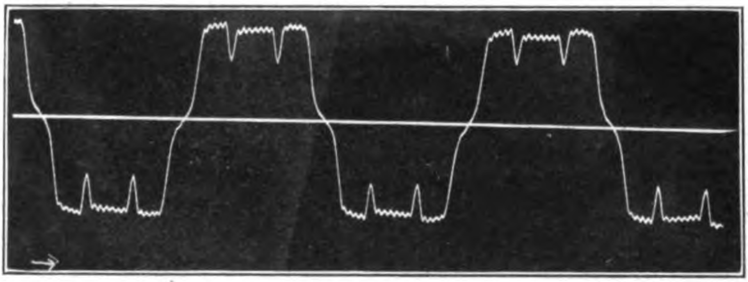

FIG. 9

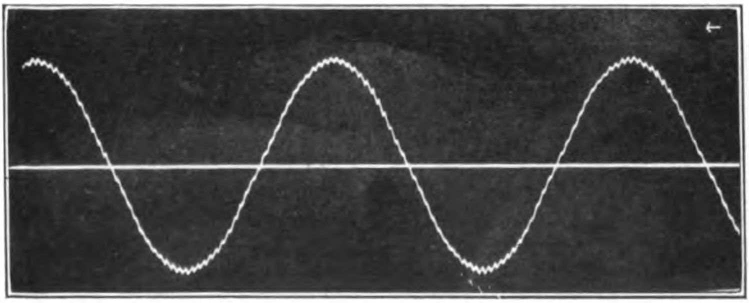

FIG. 10

with the outer sections weakened and the middle section strengthened, and Fig. 14 shows the corresponding wave shape of electromotive force; direct-current voltage 232. It will be noted that the difference in the wave shapes for these three different conditions of field excitation is scarcely perceptible. The alternating electromotive force was held constant throughout.

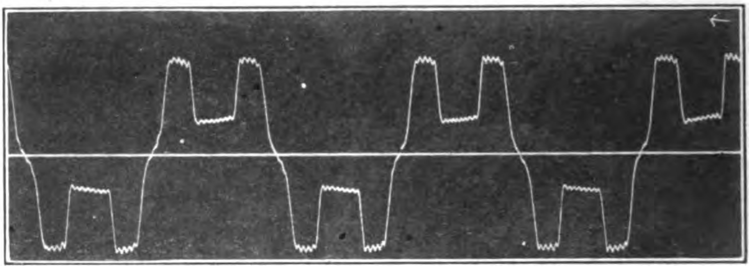

FIG. 11.

In a later development of the split-pole converter suggested by Mr. J. L. Burnham, only two pole sections are employed. One of these has a pole arc covering a considerable portion of the total pole pitch, and constitutes the principal pole, while the other covers a smaller arc and is used as an auxiliary or regulating pole. A simple explanation of the theory of this machine may be had by reference to Figs. 15 and 16. In Fig. 15 the line, *O P*, represents the alternating voltage developed by the principal pole section. The line, *O F*, may be taken to represent in amount and phase position the electromotive force developed by the auxiliary pole, these two electromotive forces being displaced by the angle, ρ, which represents the angle between the

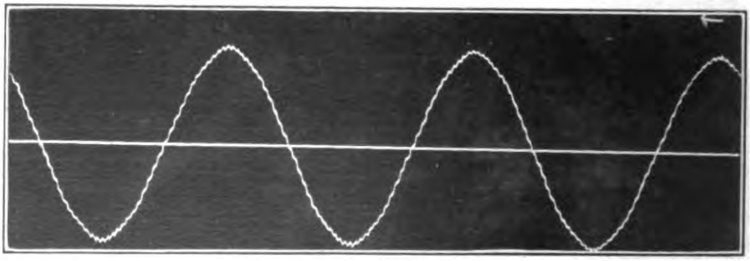

FIG. 12

axes of the two fields. The line, *O R*, will then represent the resultant alternating electromotive force. If the excitation of the auxiliary field is zero, the line, *O P*, will represent the alternating electromotive force. It will be noted that the line, *O R*, is but very little longer than the line *O P*. The direct-current electromotive force will be represented by the algebraic sum of *O P*, and *O F*. With zero excitation of the auxiliary pole this direct-current electromotive force will be represented by *O P*, while with an excitation corresponding with the line *O F*, the direct-current electromotive force will be represented by *O D*. If the main field excitation is reduced to *O P′*, when the auxiliary field has an excitation corresponding with *O F*, the resultant alternating electromotive force will be represented by *O R′*, equal to *O P*, while the direct-current electromotive force will be represented by *O D′*. It will thus be seen that the direct-current electromotive force has been increased from *O P* to *O D′* without any change in the magnitude of the alternating-

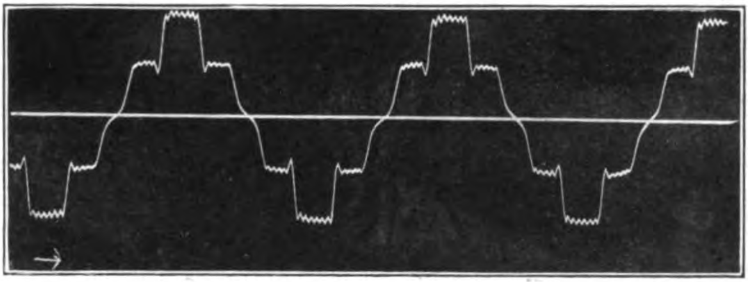

Fig. 13

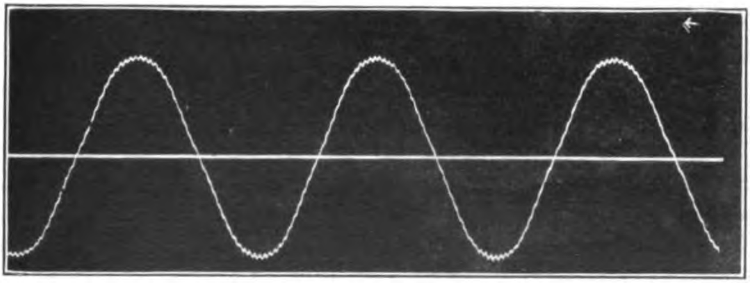

Fig. 14

current electromotive force. If the auxiliary pole be given an initial negative excitation corresponding with the line $O F_0$, such that the resultant $O R_0$ is at right angles to $O F_0$, then any variation of excitation of the auxiliary pole on either side of this point will produce a minimum change in the alternating electromotive force, provided the main field excitation is maintained constant, or will require the least variation in the excitation of the main field to maintain constant alternating electromotive force. Thus if the negative excitation of the auxiliary field be decreased to F_1, the resultant alternating electromotive force will be represented by $O R_1$, while if the negative excitation of the auxiliary pole be increased to F_2, the alternating electromotive force will be represented by $O R_2$. The corresponding direct-current electromotive forces will be represented by $O D_0$, $O D_1$, and $O D_2$, respectively. For hand control it is of course permissible to vary the excitation of both the main and auxiliary fields, in order to vary the direct-current voltage without disturbing the power-factor. With automatic control it is, however, very desirable to limit the control to a single field coil; and to accomplish this with minimum disturbance to the power factor, it is necessary to work on either side of the point F_0 which represents the mean excitation of the auxiliary pole. In Fig. 16 are illustrated the results obtained by designing the machine with a pitch of 90° between the main and auxiliary pole sections. In this case the mean excitation of the auxiliary pole for minimum change in the alternating-current electromotive force is zero, the excitation of this section being varied on either side of zero to produce a change of direct-current electromotive force above and below the mean. It can

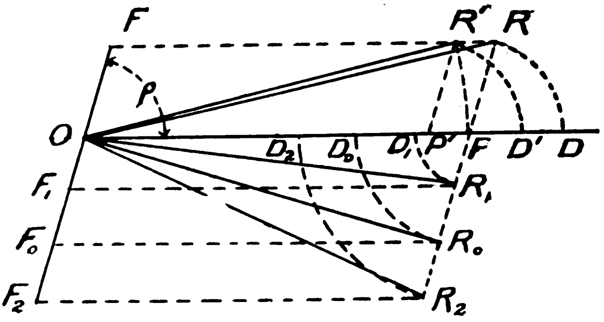

FIG. 15

be readily shown that if the lines $O F_1$, and $O F_2$, are each equal to 20 per cent. of the line $O P$, corresponding with a variation in direct-current electromotive force of 20 per cent. above and 20 per cent. below the mean, the lines $O R_1$, and $O R_2$, will be about 2 per cent. greater than the line $O P$, resulting in a total variation of 1 per cent. in the alternating electromotive force on either side of the normal.

In addition to the change in direct-current voltage it will be noted that a change in the phase position of the resultant alternating electromotive force is brought about by varying the excitation of the auxiliary pole section. If this pole section is made the trailing section, this shifting of the phase position will coöperate with the change in direct-current voltage in bringing about a quick transfer of energy between the battery and the alternating-current circuit, by advancing the phase of the alternating-current voltage, thus causing the converter to deliver energy to the alternating-current circuit at the same time that the direct-current voltage is reduced and energy is thus taken from the battery.

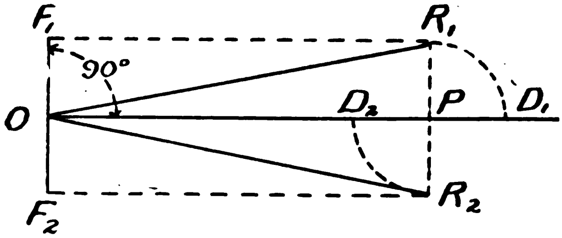

FIG. 16

The effect of the two-section split-pole construction on the wave shape of the alternating electromotive force may be determined in the following manner. Referring to Fig. 17, the line $A\ D\ B$ represents as before the developed periphery of the armature, the ordinate f representing the field density at any point, this ordinate having the values b, and c, at the face of the main and auxiliary pole sections respectively. A neutral space of 30° is allowed for commutation and the pole section pitch is taken at 90° which requires a space of 30° between the main and auxiliary pole sections. This leaves 120° for the combined arc of the two pole sections. Assuming that a variation of direct-current voltage from 20 per cent. above to 20 per cent.

below the mean is desired, and that the maximum density in the two pole sections is to be approximately the same, the arc of the auxiliary pole section should be about 20 per cent. of that of the main section. I have therefore shown the main section covering 100° of arc and the auxiliary section 20°.

Let θ represent the angular distance of any point on the circumference of the pole faces from the neutral point A which is taken as the origin.

Let f represent the ordinate corresponding with the field density at that point.

Let $X\,Y$ represent any section of the armature, having an angular span β.

Let ϕ equal the angular distance of the center point of the armature section $X\,Y$ from the origin A at any instant in the revolution in the armature.

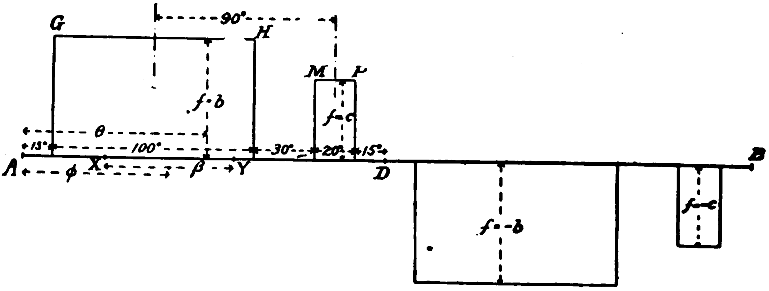

FIG. 17

Let e represent the momentary electromotive force developed in the armature section between the points X and Y at any instant.

Then by Fourier's theorem the value of f may be represented by

$$f = a_1 \sin (\theta - \alpha_1) + a_3 \sin 3\,(\theta - \alpha_3) + a_5 \sin 5\,(\theta - \alpha_5) + \; . \; . \; . + a_n \sin n\,(\theta - \alpha_n) \qquad (1)$$

Also we have

$$e = k \int_{\phi - \frac{\beta}{2}}^{\phi + \frac{\beta}{2}} f\, d\,\theta \qquad (2)$$

from which, by substituting the value of f in (1) and integrating we have

$$e = k \left\{ a_1 \left[\cos\left(\phi - \frac{\beta}{2} - \alpha_1\right) - \cos\left(\phi + \frac{\beta}{2} - \alpha_1\right)\right] + \frac{a_3}{3}\left[\cos 3\left(\phi - \frac{\beta}{2} - \alpha_3\right) - \cos 3\left(\phi + \frac{\beta}{2} - \alpha_3\right)\right] + \frac{a_5}{5}\left[\cos 5\left(\phi - \frac{\beta}{2} - \alpha_5\right) - \cos 5\left(\phi + \frac{\beta}{2} - \alpha_5\right)\right] \;.\;.\;. + \frac{a_n}{n}\left[\cos n\left(\phi - \frac{\beta}{2} - \alpha_n\right) - \cos n\left(\phi + \frac{\beta}{2} - \alpha_n\right)\right] \right\}$$

in which k is a constant depending upon the design of the machine, the speed of rotation, and the units employed. This expression may be reduced to

$$e = 2\,k \left\{ a_1 \sin\frac{\beta}{2} \sin(\phi - \alpha_1) + \frac{a_3}{3} \sin\frac{\beta}{2} \sin 3\,(\phi - \alpha_3) + \frac{a_5}{5} \sin\frac{5\beta}{2} \sin 5\,(\phi - \alpha_5) \;.\;.\;.\; + \frac{a_n}{n} \sin\frac{n\beta}{2} \sin n\,(\phi - \alpha_n) \right\} \qquad (3)$$

It will be noted that the expression within the brackets consists of the fundamental sine wave $a_1 \sin\frac{\beta}{2} \sin(\phi - \alpha_1)$ upon which is superposed a series of harmonics of the general form $\frac{a_n}{n} \sin\frac{n\beta}{2} \sin n\,(\phi - \alpha_n)$. The coefficient of each of these harmonic terms is made up of two factors, namely $\frac{a_n}{n}$ and $\sin\frac{n\beta}{2}$ whose product will determine the magnitude of the harmonic. Let us first consider the factor $\frac{a_n}{n}$. In order to determine the value of a_n, multiply both members of equation (1) by $\sin n\theta\, d(n\theta)$ and integrate between the limits $\theta = o$ and $\theta = \pi$. The second member will then consist of a series of terms of the form $\int_0^\pi a_m \sin m\,(\theta - \alpha_m) \sin n\,\theta\, d\,(n\,\theta)$.

It can be shown that $\int_0^\pi a_m \sin{}_m (\theta - \alpha_m) \sin n\,\theta\, d\,(n\,\theta) = o$ when m and n are unequal odd integers. Every term in the second member of the equation therefore reduces to zero except the one term in which m equals n and the equation reduces to

$$\int_0^\pi f \sin n\,\theta\, d\,(n\,\theta) = \int_0^\pi a_n \sin n\,(\theta - \alpha_n) \sin n\,\theta\, d\,(n\,\theta) =$$

$$\frac{n\,\pi\,a_n \cos n\,\alpha_n}{2} \tag{4}$$

To eliminate α_n assume the zero point, or origin from which the angular measurements are made, moved forward along the periphery of the pole face by an angle $\frac{\pi}{2n}$ and let θ' represent the angular distance of any point on the pole faces from this new origin. α_n will then become $\alpha_n - \frac{\pi}{2n}$ and equation (4) becomes

$$\int_0^\pi f \sin n\,\theta'\, d\,(n\,\theta') = \frac{n\,\pi\,a_n \cos\left(n\,\alpha_n - \frac{\pi}{2}\right)}{2} = \frac{n\,\pi\,a_n \sin n\,\alpha_n}{2} \tag{5}$$

Combining (4) and (5) by squaring and adding we have

$$a_n = \frac{2}{n\pi}\sqrt{\left\{\int_0^\pi f \sin n\,\theta\, d\,(n\,\theta)\right\}^2 + \left\{\int_0^\pi f \sin n\,\theta'\, d\,(n\,\theta')\right\}^2} \tag{6}$$

The value of the expression $\int_0^\pi f \sin n\,\theta\, d\,(n\,\theta)$ can readily be obtained from the flux distribution. Where f is a succession of constant values as in Fig. 17, the integration gives

$$-f \cos n\,\theta \Big|_{\text{limit}}^{\text{limit}}$$

For the fundamental wave $n = 1$, and the value of the first integral under the radical sign may be derived as follows from the data given in Fig. 17;

Limits, θ	f	Integral	Value
0° to 15°	o		
15° to 115°	b	$-b\,(\cos 115° - \cos 15°)$	$+1.3885\,b$
115° to 145°	o		
145° to 165°	c	$-c\,(\cos 165° - \cos 145°)$	$+\ .147\,c$
165° to 180°	o		
		Total	$(1.3885\,b + .147\,c)$

For the second integral assume the origin moved 90° ahead and proceed as above.

Limits, θ'	f	Integral	Value
0° to 25°	b	$-\,b\,(\cos 25° - \cos 0°)$	$+.0937\,b$
25° to 55°	o		
55° to 75°	c	$-\,c\,(\cos 75° - \cos 55°)$	$+.315\,c$
75° to 105°	o		
105° to 180°	$-b$	$+\,b\,(\cos 180° - \cos 105°)$	$-.7412\,b$
		Total	$-.6475\,b + .315\,c$

Substituting these two values in (6) we have

$$a_1 = \frac{2}{\pi}\sqrt{(1.3885\,b + .147\,c)^2 + (-\,.6475\,b + .315\,c)^2},$$

or

$$a_1 = \frac{2}{\pi}\sqrt{2.347\,b^2 + .121\,c^2} \tag{7}$$

$$\text{If } c = o \qquad\qquad a_1 = \ .975\,b$$
$$\text{If } c = +b \text{ or } -b,\ a_1 = 1.000\,b$$

Thus we have a variation of 2½ per cent. in the magnitude of the fundamental sine wave of electromotive force with a 40 per cent. change in the direct-current voltage.

To determine the value of a_5 we have $n = 5$. Proceeding as above:

Limits, θ	f	Integral	Value
0° to 15°	o		
15° to 115°	b	$-b\,(\cos 575° - \cos 75°)$	$1.078\,b$
115° to 145°	o		
145° to 165°	c	$-c\,(\cos 825° - \cos 725°)$	$+1.255\,c$
165° to 180°	o		
		Total	$1.078\,b + 1.255\,c$

Moving origin 18° ($= \pi/2n$) ahead,

Limits, θ'	f	Integral	Value
0° to 97°	b	$-b\,(\cos 485° - \cos 0°)$	$1.574\,b$
97° to 127°	o		
127° to 147°	c	$-c\,(\cos 735° - \cos 635°)$	$-.879\,c$
147° to 177°	o		
177° to 180°	$-b$	$+b\,(\cos 900° - \cos 885°)$	$-.034\,b$
		Total	$1.540\,b - .879\,c$

From which

$$a_5 = \frac{2}{5\pi}\sqrt{3.532\,b^2 + 2.347\,c^2} \tag{8}$$

If $c = o$ $a_5 = .239\,b$

If $c = +b$ or $-b$, $a_5 = .308\,b$

By the above method the value of a_n for any harmonic term for any type of synchronous machine may be determined when the field distribution is known. (For a more general solution of the two-sectional pole type, see Appendix.)

Turn now to the other factor in the coefficient, namely $\sin\frac{n\beta}{2}$. The angle β represents the angular span included between two alternating-current taps from the armature to the collector rings. When this angle is known this factor in the coefficient is determined. For the ordinary diametric connection we have $\beta = \pi$ and $\sin\frac{n\beta}{2}$ is always $\pm$ 1, n being an odd integer, and it can be shown that when $\beta = \pi$, each harmonic in the series is passing through a maximum value with respect to the fundamental. By making $\beta = \frac{2\pi}{3}$, $\sin\frac{3\beta}{2} = 0$, and the third harmonic disappears. Likewise all the multiples of the third harmonic are reduced to zero. This corresponds with the ordinary three-phase delta connection. With this value of β we have

$$\sin\frac{n\beta}{2} = \pm\tfrac{1}{2}\sqrt{3}$$

for all values of n except multiples of three. The ratio to the fundamental, of all harmonics except the third and its multiples, will therefore be the same as with the diametric connection.

The third harmonic and its multiples may however be similarly suppressed by star-connecting the primaries of the statics. By doing this the value of β may be chosen with reference to some other harmonic than the third. By making $\beta = .8\,\pi$ we have $\sin\frac{5\beta}{2} = 0$ and the 5th harmonic disappears. By making $\beta = \frac{6\pi}{7}$, $\sin\frac{7\beta}{2} = 0$ and the 7th harmonic disappears. By assuming a value for β intermediate between .8 π and $\frac{6\pi}{7}$, say .82 π, we have $\sin \frac{5\beta}{2} = .1564$ and $\sin \frac{7\beta}{2} = .397$, and both the 5th and 7th harmonics are reduced to small percentages of their maximum values.

In Fig. 18 is illustrated a combination designed to suppress the third harmonic and reduce the 5th and 7th to a minimum as above described. The armature A, of the converter is provided with alternating-current taps dividing it into three phase-sections, each spanning an angle of $.82\,\pi = 147^\circ\, 36'$. The three phase-sections are however displaced by angles of 120°, and can therefore be independently connected across the secondaries of the statics whose primaries are star-connected to the three-phase circuit as shown.

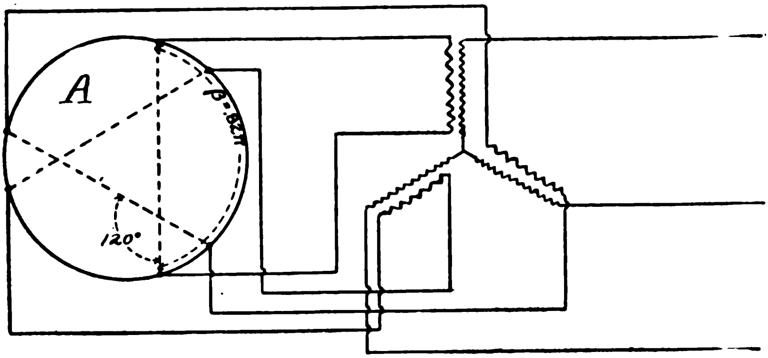

FIG. 18

From equation (3) it will be seen that the ratio of the amplitude of any harmonic to that of the fundamental is

$$\frac{a_n \sin \frac{n\beta}{2}}{a_1 \sin \frac{\beta}{2}}$$

Substituting in this the values of a_1 and a_5 as given in equations (7) and (8) and similarly determining the value of this ratio for the 7th harmonic, the values of these two harmonics in proportion to the fundamental will be given in terms of the two field densities *b* and *c*. The direct-current voltage will be proportional to the total field flux, *i.e.*, to $b + .2\,c$ (the smaller pole section arc being 20 per cent. of the greater). From these data the curves shown in Fig. 19 have been plotted, showing the ratio of the 5th and 7th harmonics to the fundamental for various direct-current voltages covering a range of 20 per cent. on each side of the mean. In the curves to the left the diametric connection has been assumed; the same ratios would hold for three-phase delta connection. In the curves to the right the relative values of the same harmonics are given, using the scheme of connection as shown in Fig. 18. In the first case the maximum values of the 5th and 7th harmonics are seen to be 6.2 per cent. and 2.5 per cent. of the fundamental, respectively, while in the latter case they are both reduced to a maximum of 1 per cent. of the fundamental.

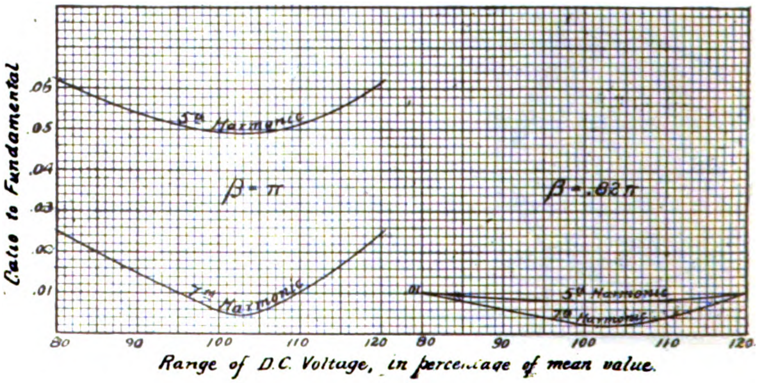

FIG. 19

In Fig. 20, is shown the resultant wave shape obtained by combining the fundamental with the 5th and 7th harmonics, the maximum values of the latter being taken, corresponding with minimum direct-current voltage and diametric connection (see Fig. 19). In Fig. 21, the wave shape is given for the same conditions except that the connections are as shown in Fig. 18 ($\beta = .82\,\pi$). In these curves, only the 5th and 7th harmonics have been considered. The 3d and 9th are eliminated by star-connecting the static primaries, and those of higher frequency may be ignored.

The scheme shown in Fig. 18, produces some increase in the heating developed in the armature winding of the converter as compared with the diametric connection. In Fig. 22, curves have been plotted showing this comparison. By reference to these curves it will be seen that the mean $I^2 R$ loss has been increased about 12 per cent., while the maximum loss in any single bar is about 50 per cent. greater than with the diametric connection. The maximum heating per slot is however increased only about 10 per cent. since the two bars in which the heating is maximum are not located in the same slot. These curves are based on field distribution corresponding to the minimum ratio of direct- to alternating-current electromotive force, the value of c in equation (7) being taken as $-b$. This voltage ratio has of course a material effect on the armature heating since it fixes the ratio between the superposed alternating and direct currents in the armature winding. The curve showing the distribution of heating with diametric phase connection in Fig. 22 is therefore somewhat different from that corresponding to a converter of normal ratio. For intermittent service, such as would be involved in storage battery regulating work, the average heating of the armature winding will usually be of minor importance, as the design of the machine would ordinarily be determined by other considerations, such as commutation at maximum momentary output and flux distribution. Thus the

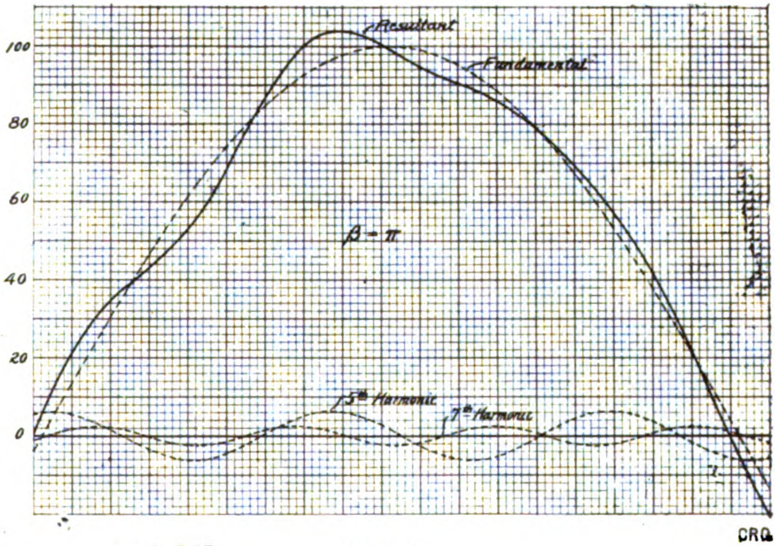

FIG. 20

scheme shown in Fig. 18 would appear to offer no appreciable disadvantages. Furthermore, this increase in heating will be at least partially offset by the reduced losses due to the elimination of high frequency currents superposed on the fundamental.

The third piece of auxiliary apparatus which I will describe is an exciter designed to control the regulating field of a booster or split-pole converter in response to variations of load on an alternating-current circuit. This machine is illustrated in Fig. 23, and as there shown consists of an armature, B, provided with a bi-polar winding revolving in a four-pole field frame. This armature is connected by suitable collector rings (not shown in the drawing) to the secondary windings of three current transformers T_1, T_2, T_3, whose primaries are connected in series with the alternating-current circuit 1, 2, 3, supplied by a source, A, whose load is to be controlled. The alternating current thus transmitted through the armature winding would, if the latter were stationary, produce a revolving field proportional to the output from the source, A. The armature is, however, rotated by means of a synchronous motor in the opposite direction to that of the field rotation so as to hold this field stationary in space. There will result a stationary field whose axis is in the line of the arrow K_1. A commutator, C,

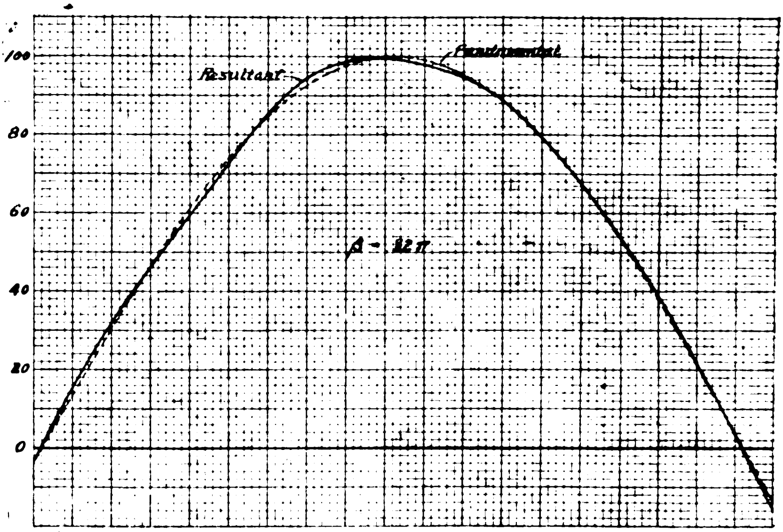

FIG. 21

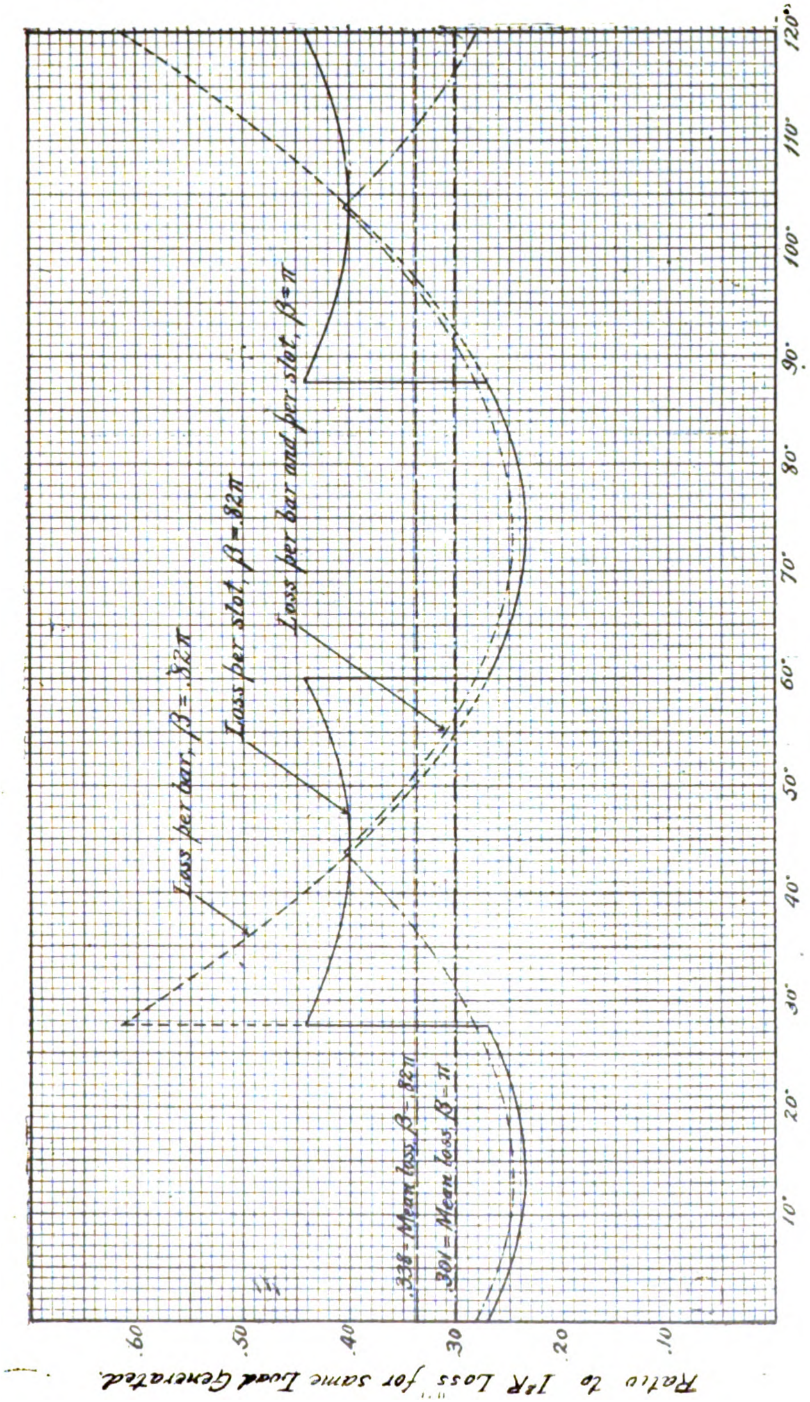
Loss per bar, $\beta = .82\pi$
Loss per slot, $\beta = .82\pi$
Loss per bar and per slot, $\beta = \pi$
.338 = Mean loss $\beta = .82\pi$
.301 = Mean loss $\beta = \pi$
.60
.50
.40
.30
.20
.10
10°
20°
30°
40°
50°
60°
70°
80°
90°
100°
110°
120°
Ratio to I^2R Loss for same Load Generated.

FIG. 22

is connected to the armature winding upon which bear two pairs of brushes, 4-5 and 6-7. The effect of the field K_1 would be to produce a direct-current electromotive force between the brushes 4 and 5. A shunt winding, 8, on the four poles of this machine, controlled by the rheostat, *R*, may be adjusted to neutralize the field K_1 at any predetermined output from the source, *A*, thus reducing the electromotive force between the brushes 4 and 5 to zero. These latter brushes are then short circuited. If now, a slight increase of load on the source *A* should occur the field K_1 would no longer be neutralized by the shunt field winding and an electromotive force would be produced between the brushes 4-5 causing a considerable flow between these brushes. This flow produces a secondary field K_2 at right angles to the first and of appreciable magnitude; and this second field produces an electromotive force across the other pair of brushes 6-7, which are connected to the regulating field, *F*. In series between the brush 7 and the corresponding terminal of the field, *F*, is connected a series winding on the poles of the exciter, designed to neutralize the magnetomotive force of the current through the armature winding between the brushes 6 and 7, so that the output from these brushes will have no disturbing effect on the exciter field.

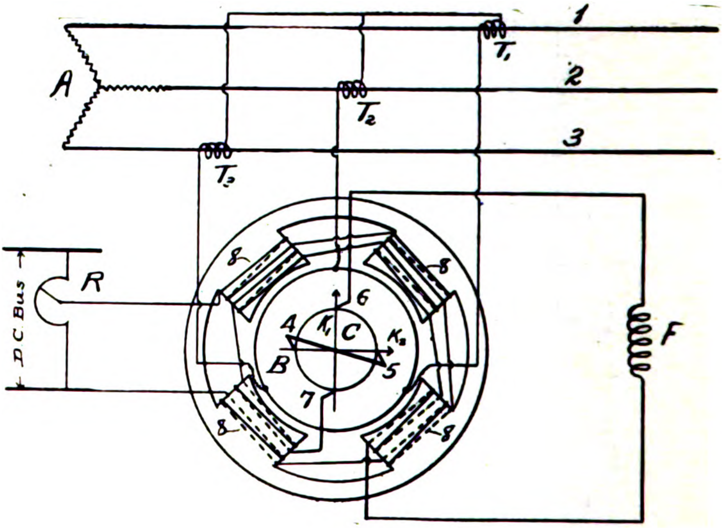

FIG. 23

This type of exciter possesses a number of important features in connection with alternating-current regulation, which may be briefly enumerated as follows:

1. It will be seen that it acts as a multiplying device by reason of the magnifying effect of the current between the short circuited brushes, and can therefore be made exceedingly sensitive to small changes in the alternating-current load.

2. It can be made to respond to any desired phase component of the alternating current by a suitable angular relation between the exciter armature and the armature of the synchronous motor which drives it. Thus for controlling the charge and discharge of a storage battery this exciter would be adjusted to respond to the energy component of the alternating current.

3. For controlling the power factor on the alternating-current circuit the two pairs of brushes 4-5 and 6-7 may be interchanged so that the latter are short-circuited while the former are connected to a field winding on any synchronous apparatus connected to the alternating-current circuit. The exciter will then be responsive to the wattless component of the alternating current and can be made to control the field of the synchronous apparatus in such a way that this apparatus will supply practically all or any desired proportion of this wattless current. For controlling both the energy fluctuations and the power-factor two such exciters may be operated, one of which is responsive to the energy component and the other to the wattless component of current.

Another advantageous feature of this exciter lies in the fact that the secondaries of the current transformers may be short-circuited at any time with the result of merely killing the regulating function. It is not necessary to disconnect the connections to the collector rings before doing this, even with considerable excitation in the shunt field winding of the exciter, since the armature reaction is so great that a short-circuit will produce only a nominal flow of current sufficient to demagnetize the fields. Similarly, in putting the apparatus into service the rheostat, *R*, if properly calibrated may be set for any desired constant load on the source, *A*, and after all the main connections are closed so that the battery is merely floating on the system, the short-circuiting switch across the secondaries of the current transformers may be opened and the load on the source, *A*, will immediately be held at the constant predetermined value for which the rheostat, *R*, has been set.

APPENDIX

A more general solution for the wave shape of alternating electromotive force in the split-pole converter of the two section type is given below, using the nomenclature shown in Fig. 24 as follows:

γ_b = the arc covered by the principal pole section.
γ_c = the arc covered by the auxiliary pole section.
$2\,\delta$ = the neutral arc between pole tips.
ρ = the pole section pitch.
θ = the angular distance of any point on the pole faces from the origin A.
$\theta' = \theta - \dfrac{\pi}{2n}$ = the angular distance of the same point from the secondary origin O.

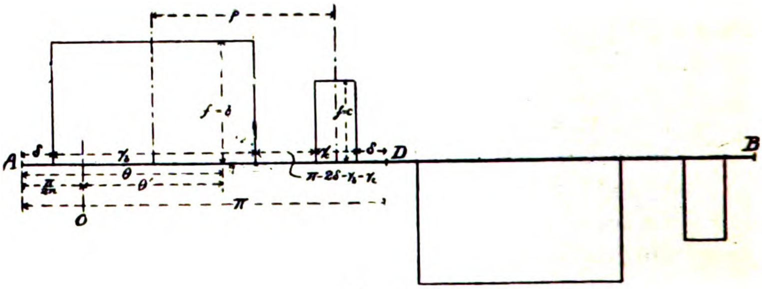

FIG. 24

b = the flux density under the principal pole section.
c = the flux density under the auxiliary pole section.

Repeating equation (6) we have

$$a_n = \frac{2}{n\pi}\sqrt{\left\{\int_0^{\pi} f \sin n\theta\, d(n\theta)\right\}^2 + \left\{\int_0^{\pi} f \sin n\theta'\, d(n\theta')\right\}^2} \qquad (6)$$

But the expression $\int_0^{\pi} f \sin\ n\theta\ d(n\theta)$, after integrating and substituting the values in Fig. 24 becomes

$$b\,[\cos n\delta - \cos n(\delta + \gamma_b)] + c\,[\cos n(\pi - \delta - \gamma_c) - \cos n(\pi - \delta)]$$
$$= b\,[\cos n\delta - \cos n(\delta + \gamma_b)] + c\,[\cos n\delta - \cos n(\delta + \gamma_c)]$$

likewise $\int_0^{\pi} f \sin n\,\theta' \, d\,(n\,\theta')$ becomes

$$b\left\{1-\cos n\left(\delta+\gamma_b-\frac{\pi}{2n}\right)\right\}+c\left\{\cos n\left(\pi-\delta-\gamma_c-\frac{\pi}{2n}\right)-\right.$$

$$\left.\cos n\left(\pi-\delta-\frac{\pi}{2n}\right)\right\}-b\left\{\cos n\left(\pi+\delta-\frac{\pi}{2n}\right)+1\right\}$$

$$=b\,[\sin n\delta-\sin n(\delta+\gamma_b)]-c\,[\sin n\delta-\sin n(\delta+\gamma_c)]$$

Substituting these values in equation (6) and making the necessary trigonometrical transformations, remembering that

$$\rho=\pi-2\,\delta-\frac{\gamma_b+\gamma_c}{2}$$

we have

$$a_n=\frac{4}{n\pi}\sqrt{b^2\sin^2\frac{\delta\ n\gamma_b}{2}+c^2\sin^2\frac{\delta\ n\gamma_c}{2}+2\,b\,c\sin^2\frac{n\gamma_b}{2}\sin^2\frac{n\gamma_c}{2}\cos n\rho} \tag{9}$$

this gives for the amplitude of any harmonic in equation (3)

$$\frac{8k}{\pi n^2}\sin\frac{n\beta}{2}\sqrt{b^2\sin^2\frac{n\gamma_b}{2}+c^2\sin^2\frac{n\gamma_c}{2}+2\,b\,c\sin\frac{n\gamma_b}{2}\sin\frac{n\gamma_c}{2}\cos n\rho} \tag{10}$$

and representing the ratio of any harmonic to the fundamental by h we have

$$h=\frac{1}{n^2}\frac{\sin\frac{n\beta}{2}}{\sin\frac{\beta}{2}}\sqrt{\frac{b^2\sin^2\frac{n\gamma_b}{2}+c^2\sin^2\frac{n\gamma_c}{2}+2\,b\,c\sin\frac{n\gamma_b}{2}\sin\frac{n\gamma_c}{2}\cos n\,\rho}{b^2\sin^2\frac{\gamma_b}{2}+c^2\sin^2\frac{\gamma_c}{2}+2\,b\,c\sin\frac{\gamma_b}{2}\sin\frac{\gamma_c}{2}\cos\rho}} \tag{11}$$

This expression gives the relative value of any harmonic in terms of the two pole section arcs γ_b and γ_c, the corresponding field strengths b and c, the pole section pitch ρ and the angular span of the armature section β. Equation (11) may also be written

$$h = \frac{1}{n^2}\,\frac{\sin\frac{n\beta}{2}}{\sin\frac{\beta}{2}}\sqrt{\frac{\sin^2\frac{n\gamma_b}{2}+\frac{c^2}{b^2}\sin^2\frac{n\gamma_c}{2}+\frac{2c}{b}\sin\frac{n\gamma_b}{2}\sin\frac{n\gamma_c}{2}\cos n\rho}{\sin^2\frac{\gamma_b}{2}+\frac{c^2}{b^2}\sin^2\frac{\gamma_c}{2}+\frac{2c}{b}\sin\frac{\gamma_b}{2}\sin\frac{\gamma_c}{2}\cos\rho}} \tag{12}$$

in which the ratio of the harmonic to the fundamental is expressed in terms of the ratio between the field strength of the auxiliary section and that of the principal section.

Let $b = b_0$ when $c = 0$, also let the amplitude of the fundamental electromotive force be kept constant by slightly varying the value of b as c is varied. Then from equation (9) we have

$$b^2\sin^2\frac{\gamma_b}{2}+c^2\sin^2\frac{\gamma_c}{2}+2\,b\,c\sin\frac{\gamma_b}{2}\sin\frac{\gamma_c}{2}\cos\rho = b_0^2\sin^2\frac{\gamma_b}{2} \tag{13}$$

Substituting this in equation (11) we have

$$h = \frac{1}{n^2}\cdot\frac{\sin\frac{n\beta}{2}}{\sin\frac{\beta}{2}}\cdot\frac{\sqrt{\frac{b^2}{b_0^2}\sin^2\frac{n\gamma_b}{2}+\frac{c^2}{b_0^2}\sin^2\frac{n\gamma_c}{2}+\frac{2bc}{b^2_0}\sin\frac{n\gamma_b}{2}\sin\frac{n\gamma_c}{2}\cos n\rho}}{\sin\frac{\gamma_b}{2}} \tag{14}$$

For any assumed value of c/b_0 the value of b/b_0 may be determined from equation (13) and these two in (14) will give the corresponding value of h.

The direct current voltage V will be (see equation 2)

$$V = k\int_0^\pi f\,d\,\theta$$

and using the nomenclature in Fig. 24, this becomes

$$V = k\left\{b\,\gamma_b + c\,\gamma_c\right\} \tag{15}$$

From (10) the mean effective value of the fundamental is

$$E = \frac{4\,k\sqrt{2}}{\pi}\sin\frac{\beta}{2}\sqrt{b^2\sin^2\frac{\gamma_b}{2}+c^2\sin^2\frac{\gamma_c}{2}+2\,b\,c\sin\frac{\gamma_b}{2}\sin\frac{\gamma_c}{2}\cos\rho} \tag{16}$$

and the ratio of alternating- to direct-current voltage

$$\frac{E}{V}=\frac{4\sqrt{2}}{\pi\,(b\,\gamma_b+c\,\gamma_c)}\sin\frac{\beta}{2}\sqrt{b^2\sin^2\frac{\gamma_b}{2}+c^2\sin^2\frac{\gamma_c}{2}+2\,b\,c\sin\frac{\gamma_b}{2}\sin\frac{\gamma_c}{2}\cos\rho} \tag{17}$$

or

$$\frac{E}{V}=\frac{4\sqrt{2}}{\pi\left(\gamma_b+\frac{c}{b}\gamma_c\right)}\sin\frac{\beta}{2}\sqrt{\sin^2\frac{\gamma_b}{2}+\frac{c^2}{b^2}\sin^2\frac{\gamma_c}{2}+2\frac{c}{b}\sin\frac{\gamma_b}{2}\sin\frac{\gamma_c}{2}\cos\rho} \tag{18}$$

which gives this ratio in terms of the ratio c/b

I $c = o$, (17) becomes

$$\frac{E_0}{V_0}=\frac{4\sqrt{2}}{\pi\,\gamma_b}\sin\frac{\beta}{2}\sin\frac{\gamma_b}{2} \tag{19}$$

If the amplitude of the fundamental is held constant, we have $E = E_0$ and by substituting (13) and (19) in equation (17)

$$V = V_0\left\{\frac{b}{b_0}+\frac{c}{b_0}\cdot\frac{\gamma_c}{\gamma_b}\right\} \tag{20}$$

From equations (13) and (20) the variation of the direct-current electromotive force may be derived for any change in the auxiliary field strength, on the assumption that the alternating-current electromotive force is held constant by varying the strength of the principal pole section. If the converter is connected to a source of constant alternating electromotive force, this variation in the field strength of the principal pole section, if not obtained by manual adjustment, will be brought about by the magnetizing effect of the wattless currents in the armature winding.

From equations (13), (14), and (20), the curves shown in Fig. 19 were obtained.

In Fig. 25 curves have been plotted giving the variation in field strength of the main and auxiliary poles for various direct-current voltages, the amplitude of the fundamental wave of alternating electromotive force being held constant, these curves being plotted from equations (13) and (20), the following values (corresponding to the design of a machine actually built) being assumed for the pole face arcs:

$$\gamma_b = 104^\circ$$
$$\gamma_c = 44^\circ$$
$$\rho = 74^\circ$$

It will be noted that a certain maximum direct-current voltage is reached which cannot be exceeded under the condition of constant alternating electromotive force, since the reduction in the main field strength necessary to maintain this latter condition more than offsets the further increase in the auxiliary field strength. It will also be noted that over a wide range of variation of the direct-current voltage the main field strength remains nearly constant, passing through a maximum point

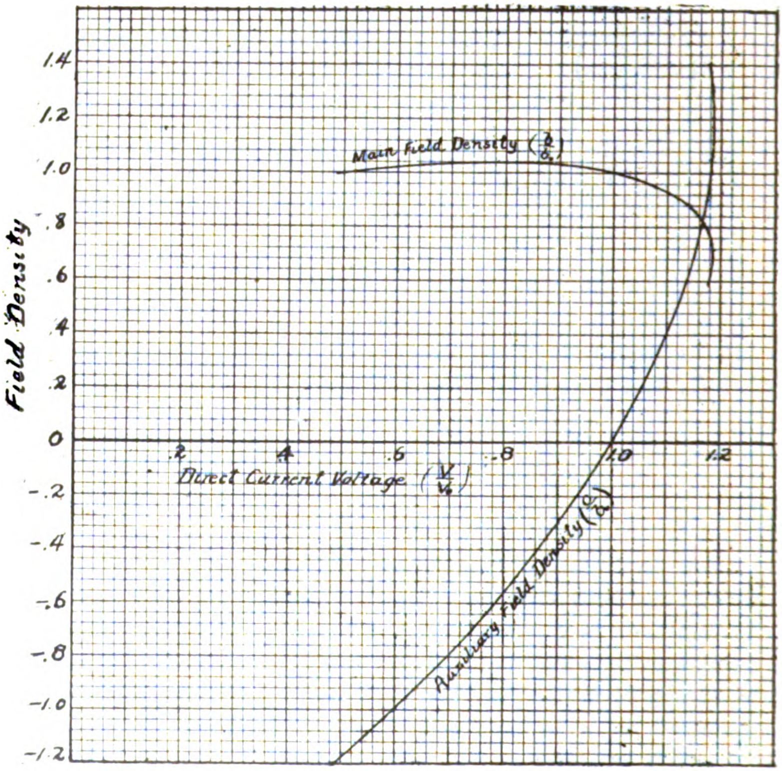

FIG. 25

from which it recedes as the direct-current voltage is increased or diminished.

By reference to equation (12) it will be seen that certain of the harmonics may be eliminated by giving suitable values to γ_b and γ_c. For example, if $\gamma_b = \frac{4\pi}{7}$ and $\gamma_c = \frac{2\pi}{7}$, the 7th harmonic will disappear. These values for the pole section arcs leave but very little neutral area for commutation, even if the pole sections are contiguous, and call for an auxiliary pole section arc one-half that of the principal pole section, while the angle ρ is $\frac{3\pi}{7}$, necessitating control of both pole sections in order to maintain unity power factor (unless the mean value of c is negative, which will reduce the kw. output). The 5th harmonic cannot be entirely eliminated in this way, and the higher harmonics are not of sufficient importance to warrant a design which is otherwise disadvantageous.

Some of the higher harmonics may also be suppressed by using a fractional pitch winding. This method however cannot be carried far enough to have an appreciable effect on the value of harmonics below the 9th.

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THE RELATIVE PROPORTIONS OF COPPER AND IRON IN ALTERNATORS

BY CARL J. FECHHEIMER

Many radical changes have accompanied the rapid development of alternating-current generators. In the early days, when alternators were designed by rule-of-thumb methods, the relative proportion of copper to iron was high. These machines had very poor inherent regulation, and in many cases failed to give the voltage for which they were designed. These " copper machines " were relatively light, and were considerably cheaper than the " iron machines " which succeeded them. The iron machines, though much heavier and more expensive than their predecessors, had much better regulation. Following this, the characteristics of alternators were more carefully studied so that the designer was able to reduce the weight and again approach the copper machine. Competition between the various manufacturing companies made it necessary for their engineers to design cheaper machines, resulting in a compromise between the " copper " and " iron " machines. We are now at this period, and the designer is to-day confronted with the question: what shall be the relative proportions of copper and iron in this machine? Doubtless the answer is, so to proportion the iron and copper as to obtain the cheapest possible machine.

The usual method of carrying this out consists in designing a number of machines with different fluxes, and possibly different diameters, and, after calculating the weights and costs of the various parts, to select that design which is believed to be the most desirable. This method requires a great amount of time, and is very laborious. In this paper the writer has endeavored to bring out a method which will enable the designer to determine, after a few substitutions, what value of flux to employ to give the cheapest machine. He has made no attempt to determine mathematically the best diameter to use; in fact, he has assumed certain simple relations involving the diameter, such as the ratio of pole axial length to pole pitch. However, the relations are such that the designer, having studied and designed a number of machines in the past, can readily decide upon the best values to use for these constants.

So many variables enter into the design of alternators that it has been essential to establish definite relations between some of them in order to reduce their number. Some of these relations are empirical, in which case the evaluation of the constants involved in the empirical equations is left to the designer. Other relations, such as the fundamental equation used for determining the temperature rise of the armature coils, and the relation between field and armature ampere-turns per pole, are combinations of fundamental principles with empirical constants.

Briefly, the method which the writer has pursued in this paper is as follows: Equations are derived for the weights of the principal parts of the alternator, the weight in each case being expressed as some factor which is easily determined, multiplied by some power of the flux per pole. The weight of these parts is then multiplied by the price per pound of material used and by some other factor to allow for the unavoidable scrap material, and also for some of the parts not included in the equations, as for example, the stator teeth and the spider arms. The sum of these costs will give the cost of the material in the principal parts of the machine in terms of the flux. We can find what value of flux to employ to give the minimum cost of material in the parts considered by differentiating the equation obtained with respect to the flux, equating to zero, and solving the equation for the flux. Having determined the flux, the number of conductors necessary to give the desired electromotive force at once follows. The arrangement of these conductors, the diameter and length of the machine, the dimensions of the field conductor, etc., are left to the judgment of the designer, as has been the custom in the past.

The method is intended to apply to revolving-field alternators having rectangular poles. It is quite possible, however, to apply the method to machines of the revolving-armature type, although, judging from present indications, this type of machine will be built very little in the future. The round-pole machine necessitates so large a diameter that the cost of this type of machine would generally be much greater than the rectangular pole machine, even though there would be a considerable saving in field copper. There are special cases in which the round-pole machine is desirable, and in such cases it would be possible to modify the equations as derived by the writer.

The cost of the bases, shafts, bearings, and other "dead" material increases somewhat with the flux, but it is impossible to consider every detail in determining the most suitable value of flux to use. The labor also increases somewhat with the flux. As this is usually much smaller than the material, it has been neglected in the method which has been employed. The freight also increases with the quantity of flux employed, as a large flux machine means a machine that will be great in weight. All things considered, it will usually be best, from the standpoint of cost, to select a value for the flux which will be slightly less than that given by means of the equations.

If we were to employ a value of flux as given by the equation for the cheapest machine, it would be impossible in some cases, with our present methods of cooling, to prevent an excessive temperature rise, as, for example, in some of the small, high-speed, 25-cycle machines. In these, the fields become so crowded near the bases of the poles that it is very difficult to put sufficient copper in the fields to keep their temperature rise within limits, especially when the machine is to operate at low power-factor. In such cases, the best we can do is to approach as near to the copper machine as possible. In a few other cases there are limits which prevent the direct application of the writer's method.

In some cases it is possible to reduce the weight below the weight of the cheapest machine as determined by the writer's method, without sacrificing the electrical qualities of the machine. In such cases it may be advisable to build the lightest machine rather than the machine which will be the cheapest for the factory to build, especially when the machine is to go to some district to which the freight rates are very great.

The method is only an approximation, but is believed by the writer to be sufficiently accurate for commercial purposes; for when we consider the variation in weight of yoke castings made from the same pattern, the not inconsiderable difference in temperature rise of duplicate machines, and the wide limits between which the market value of the raw material fluctuates (copper in particular), a rough approximation is doubtless sufficiently accurate.

As previously stated, no attempt has been made to determine mathematically the best diameter and axial length to employ. Within reasonable limits, a decrease in diameter (and increase in length) usually necessitates an increase in copper and a reduction in iron and total weight. Conversely, an increase in diameter requires an increase in total iron and a reduction in copper. This follows from the well known facts that the ventilation in a long machine is poorer than in a short machine; that the field mean-turn is greater in the former than in the latter; that the weight of the yoke and spider increase more rapidly with an increase in diameter than with an equivalent increase in length, etc. The labor is usually slightly less on the machine having the small diameter. The freight is generally less on the small diameter machine. There are some cases, as in engine-type, 60-cycle generators of small output, in which the machines must be made large in diameter to prevent so small a pole pitch as to cause the field to become too crowded. On the other hand, the diameter is often limited by the peripheral speed. The choice of diameter and length of machine depend upon the judgment of the designer.

The writer appreciates the fact that a mathematical treatment of this kind has a tendency to cause the designer to drift away from the physical conception of the problem in hand. The designer can, however, check up his calculations roughly as he proceeds, by comparing the weight of each part with the weight of corresponding parts of machines previously built, he having assumed an approximate value for the flux. He can further simplify his calculations by plotting curves. For example, he can plot a series of curves to aid him in evaluating K^{x} in equation (42). He may plot K^{x} against the number of poles, p, fixing the value of K^{II} K^{IV}, and plotting different curves for different values of B_a, the armature core density.

NOTATION

a = number of active conductors per slot = number of conductors per slot divided by number of parallel circuits in armature.

A = ampere conductors per inch of armature periphery, full load.

B_a = flux density in armature core in kilolines per sq. in.

$B_{f.r.}$ = flux density in field ring in kilolines per sq. in.

B_P = flux density in poles in kilolines per sq. in.

d_1 = outside diameter of field ring in inches.

d_2 = inside diameter of field ring in inches.

D_1 = outside diameter of armature laminations, in inches.

D_2 = inside diameter of armature laminations, in inches.

E = alternating-current electromotive force per phase or per leg if star connected.

E' = direct-current exciting electromotive force per pole.

F_a = equivalent section in square inches of one active armature conductor = section of one conductor multiplied by the number of parallel paths in armature.

F_f = section in square inches of field conductor.

H = radial dimension of pole including head.

I_a = alternating current amperes per leg in armature.

I_f = direct current amperes excitation on full field.

k = distribution factor = ratio of vector to algebraic sum of electromotive forces induced in armature conductors in one leg.

K = ratio of net to gross iron in poles.

K' = ratio of field ampere-turns per pole required for full field to the armature ampere conductors per pole with full load.

K^{II} = ratio of W to λ (ratio of tangential dimension of pole to axial length of pole).

K^{III} = resistivity in micro-ohms of an inch cube of copper at the temperature of the fields when hot = .85 approx.

K^{IV} = ratio of pole length λ to pole pitch τ

$$K^{V} = \frac{3130\ K^{III}\ \sigma}{K\ B_P\ P_f}\ \frac{(K^{II}+1)^2}{K^{II}}\left[\frac{P_a\ K'}{k\ \sim}\right]^2$$

K^{VI} = factor by which the product of amperes per square inch and ampere conductors per inch should be divided to give the temperature rise in degrees centigrade of armature coils.

K^{VII} = ratio of length of armature end connections per coil to pole pitch.

$$K^{VIII} = \frac{323\times10^6\ (2\ K^{IV}+K^{VII})}{p\ T\ K^{VI}}\left[\frac{P_a}{\sim\ k}\right]^2$$

K^{IX} = ratio of net iron in armature to axial length of pole λ.

K^{X} $= \dfrac{22{,}000}{B_a}\sqrt{\dfrac{K\,K^{\text{II}}\,B_{\text{P}}}{10\,\sigma}}\left(\dfrac{1}{B_a\,K^{\text{IX}}}+\dfrac{0.636\,p\,\sigma}{K\,K^{\text{II}}\,K^{\text{IV}}\,B_{\text{P}}}\right)$

K^{XI} = coefficient used for determining weight of yoke =

$$\frac{W_y}{D_1^{\frac{5}{4}}\,L^{\frac{1}{4}}}$$

K^{XII} $= 565\,K^{\text{XI}}\sqrt{\dfrac{p}{K^{\text{IV}}}}\left[\dfrac{.318\,\sigma\,p}{K\,K^{\text{II}}\,K^{\text{IV}}\,B_{\text{P}}}+\dfrac{1.5}{K^{\text{IX}}\,B_a}\right]$

K^{XIII} = ratio of pole radial heighth H, to square root of pole waist W.

K^{XIV} $= 1580\,p\,K^{\text{XIII}}\,(K^{\text{II}}/K)^{\frac{1}{4}}\,(\sigma/B_{\text{P}})^{\frac{5}{4}}$

K^{XV} $= \dfrac{4450\,\sigma'}{B_{f.r.}}\sqrt{\dfrac{K\,K^{\text{II}}\,B_{\text{P}}}{\sigma}}\left(\dfrac{p\,\sigma}{K\,K^{\text{II}}\,K^{\text{IV}}\,B_{\text{P}}}-\dfrac{1.57\,\sigma'}{B_{f.r.}}\right)$

K^{XVI} $= \dfrac{4900\,\sigma'}{B_{f.r.}}\,K^{\text{XIII}}\left(\dfrac{\sigma\,K^{\text{II}}}{K\,B_{\text{P}}}\right)^{\frac{1}{4}}$

$(M.T.)_a$ = mean length of turn, in inches, of armature coil.
$(M.T.)_f$ = mean length of turn, in inches, of field coil.
N = number of field turns per pole.
n = number of phases.
p = number of poles.
p_a = price, in dollars per pound, of armature copper, including transportation, etc.
p_{ai} = price, in dollars per pound, of armature active iron, including transportation, etc.
p_f = price, in dollars per pound, of field copper, including transportation, etc.
$p_{f.r.}$ = price, in dollars per pound, of field ring material, including transportation, etc.
p_{P} = price, in dollars per pound, of pole iron, including transportation, etc.
p_y = price, in dollars per pound, of yoke iron, including transportation, etc.
P_a = rated kilovolt-ampere output of alternator.

P_f = kilowatts excitation required for full field on alternator.
S = number of stator slots per phase per pole.
S_a = cost of armature copper in dollars.
S_{ai} = cost of armature active iron in dollars.
S_f = cost of field copper in dollars.
S_m = cost of material for principal parts of alternator in dollars.
$S_{f.r.}$ = cost of field ring in dollars.
S_p = cost of poles in dollars.
S_y = cost of yoke in dollars.
T = temperature rise in degrees centigrade, of armature coils.
W = pole waist, or tangential dimension of pole.
W_a = weight in pounds of armature copper.
W_{ai} = weight in pounds of armature active iron.
W_f = weight in pounds of field copper.
$W_{f.r.}$ = weight in pounds of field ring.
W_p = weight in pounds of poles.
W_y = weight in pounds of yoke.
X = full field ampere-turns per pole.

GREEK LETTERS

α_1 = $p_f \, K^{\mathrm{v}}$
α_2 = $p_a \, K^{\mathrm{viii}}$
α_3 = $p_{ai} \, K^{\mathrm{x}} + p_{f.r.} \, K^{\mathrm{xv}}$
α_4 = $p_y \, K^{\mathrm{xii}}$
α_5 = $p_p \, K^{\mathrm{xiv}} - p_{f.r.} \, K^{\mathrm{xvi}}$
Δ = current density in armature copper, amperes per square inch
λ = length of pole parallel to shaft.
σ = pole leakage factor = $\dfrac{\text{flux in one pole}}{\text{useful flux per pole.}}$
σ' = field ring leakage factor.
τ = pole pitch in inches.
ϕ = flux in megalines per pole.
$\sim$ = frequency, cycles per second.

WEIGHT AND COST OF MATERIAL REQUIRED FOR ALTERNATORS.

FIELD COPPER

We have the following well-known fundamental equations:

$$\phi = \frac{100\,E}{2.22\,a\,S \sim p\,k} \tag{1}$$

$$A = \frac{a\,S\,I_a\,n}{\tau} \tag{2}$$

$$B_P = \frac{10^3\,\phi\,\sigma}{W\,\lambda\,K} \tag{3}$$

Combining the above equations, we have:

$$\phi = \frac{100\,E\,I_a\,n}{2.22\,p\,k \sim A\,\tau} = \frac{W\,\lambda\,B_P\,K}{10^3\,\sigma} \tag{4}$$

The ratio of the field ampere-turns per pole required for full field to the armature ampere conductors per pole is fixed, within reasonable limits, by the regulation required of the alternator, the power-factor of the circuit, the amount of overload required of the generator, and the manner in which the magnetic circuit is proportioned; it being understood that the alternator is to give its normal voltage when operating at the proper frequency and subjected to the specified overload at the power-factor of the circuit. This ratio varies from 1 to 2.2 in polyphase machines, depending upon the factors given above, and in accordance with guarantees required by consulting engineers at the present time. Calling this ratio K', we have:

$$X = K'\,A\,\tau \tag{5}$$

Combining (4) and (5),

$$X = \frac{10^5\,E\,I_a\,n\,K'\,\sigma}{2.22\,p\,k \sim W\,\lambda\,B_P\,K}$$

But $E\,I_a\,n = 10^3\,P_a$ (6)

Therefore,

$$X = \frac{10^8\,P_a\,K'\,\sigma}{2.22\,p\,k \sim W\,\lambda\,B_P\,K} \tag{7}$$

The following equations are well known:

$$F_f = \frac{K'''\,X\,(M.T.)_f}{10^6\,E'} \tag{8}$$

$$W_f = 0.318\,(M.T.)_f\,N.\,p\,F_f \tag{9}$$

And the following is sufficiently accurate for the present estimate, when the poles are rectangular in section:

$$(M.T.)_f = 2.2\ (W + \lambda) \tag{10}$$

Combining (8), (9) and (10),

$$W_f = \frac{1.54\ K^{III}\ X\ p\ N\ (W + \lambda)^2}{10^6\ E'} \tag{11}$$

The designer will know approximately at the start what the ratio of the tangential dimension, W, of the pole, to the axial length of the pole, will be. This ratio varies from 1 in high speed 25 cycle machines to 4.0 in slow speed 60 cycle generators. Calling this ratio K^{II}, we have

$$W = K^{II}\ \lambda \tag{12}$$

The amperes excitation on full field is:

$$I_f = \frac{X}{N} \tag{13}$$

Combining (11), (12) and (13),

$$W_f\ I_f = \frac{1.54\ (K^{II} + 1)^2\ \lambda^2\ p\ K^{III}\ X^2}{10^8\ E'} \tag{14}$$

Combining (7) and (14),

$$W_f\ (I_f\ E'\ p) = 31.3\ K^{III}\ (K^{II} + 1)^2\ \lambda^2\ 10^8 \left(\frac{P_a\ K'\ \sigma}{k \sim W\ \lambda\ B_P\ K}\right)^2 \tag{15}$$

But

$$I_f\ E'\ p = 10^3\ P_f \tag{16}$$

and from (3),

$$W\ \lambda\ B_P\ K = 10^3\ \sigma\ \phi \tag{17}$$

The designer will recognize the fact that the ratio of pole length to pole pitch is very nearly fixed, varying from .5 in high speed 25 cycle machines to 2 in slow speed 60 cycle machines. Calling this ratio K^{IV}, we have

$$\lambda = K^{IV}\ \tau \tag{18}$$

Combining (12) and (18),

$$W = K^{\text{II}} K^{\text{IV}} \tau \tag{19}$$

Combining (3), (18) and (19),

$$\lambda = 10 \sqrt{\frac{10 \phi \sigma}{K^{\text{II}} K B_{\text{P}}}} \tag{20}$$

Combining (15), (16), (17) and (20),

$$W_f P_f = \left\{ \frac{3130 K^{\text{III}} \sigma}{K B_{\text{P}}} \frac{(K^{\text{II}} + 1)^2}{K^{\text{II}}} \left[\frac{P_a K'}{\sim k} \right]^2 \right\} \frac{1}{\phi} \tag{21}$$

Equation (21) illustrates a condition with which designers are familiar; that is, without sacrificing the good qualities of the generator, the excitation can be reduced only at the expense of field copper; and if we approach a copper machine by decreasing the flux, it results in a proportional increase in weight of field copper for a given excitation.

It is usually known at the start what full field excitation to allow, this being limited in some cases by heating; while in other cases it is necessary to reduce the excitation to prevent its becoming too large a percentage of the output of the alternator. As typical examples of the first class, we have the moderate and high speed 25 cycle alternators up to about 500 kw. output, in which the output of the machine must be reduced to prevent excessive field heating when operating at low power factors. As examples of the second class we have fairly large (1000 kw. or over) engine-type, 60-cycle generators, the field heating of which seldom exceeds 40 degrees rise when operating on full field, the single layer edge-wound field being used in both cases. Therefore, the designer, knowing the full field excitation in kilowatts at the start (having made a study of the limiting conditions), will know the value of all of the quantities in equation (21), except the flux ϕ and the weight of field copper W_f. Hence,

$$W_f = \left\{ \frac{3130 K^{\text{III}} \sigma}{K B_{\text{P}} P_f} \frac{(K^{\text{II}} + 1)^2}{K^{\text{II}}} \left[\frac{P_a K'}{\sim k} \right]^2 \right\} \frac{1}{\phi} \tag{22}$$

And $$W_f = K^{\text{v}} \frac{1}{\phi} \tag{23}$$

Where K^{v} is the expression in the brace in equation (22).

If p_f represent the price in dollars of one pound of field copper, the total cost of field copper for the alternator is:

$$S_f = p_f K^{\text{v}} \frac{1}{\phi} \tag{24}$$

ARMATURE COPPER.

The weight of copper required for the armature of an alternator depends primarily upon the temperature rise per watt loss per square inch of radiating surface. The loss is not only affected by the core loss and copper loss due to the resistance of the copper, but also by the eddy-current loss in the copper. The core loss differs considerably in duplicate machines, due chiefly to variation in material. All revolving-field alternators depend for the cooling of their armatures upon the air thrown into the stator by the rotating element. It frequently happens that this air is not uniformly distributed over the surface of the armature, causing a greater cooling at one side than at the other side of the armature, resulting in a greater elevation in temperature in one part of the armature than in another. The designer must allow for the maximum elevation in temperature. With the inconsistent data obtained from heat runs on a large number of machines, it is next to impossible to obtain any reliable means of predetermining the temperature rise within a few per cent. The best that can be done is to obtain a rough approximation. Machines having the same quantity of air thrown upon each square inch of stator surface per unit of time, and when worked at the same magnetic densities in the stator, will, when operated on open circuit, have approximately the same elevation on the stator iron. It is therefore reasonable that the incremental heating due to the copper loss be alone considered.

It may be easily shown that the watts copper loss (due to resistance only) per square inch of surface is proportional to the product of ampere-conductors per inch and the current density in the armature conductor (in amperes per square inch). The surface is taken as the cylindrical surface of the armature iron plus the surface of the end-connections. Hence, we may write:

$$T = \frac{A\,\Delta}{K^{\text{vi}}} \tag{25}$$

T is the temperature rise in degrees centigrade, A the ampere conductors per inch, and Λ the density in amperes per square inch. K^{VI} varies in values from 1.8×10^4 in poorly ventilated, or slow speed, high voltage machines to 9×10^4 in low-voltage, well ventilated machines, not having appreciable eddy current loss in the conductors. These values of K^{VI} are consistent with modern practice in methods employed in cooling the stators of revolving field alternators. If at some future time the methods of cooling are improved, K^{VI} should be modified accordingly.

Since
$$\Lambda = \frac{I_a}{F_a}, \tag{26}$$

where I_a = alternating current amperes per leg, and F_a = section of one active armature conductor, we have, by combining with (2) and (25),

$$a\,S = \frac{T\,F_a\,K^{\text{VI}}\,\tau}{I_a^2\,n} \tag{27}$$

The weight of armature copper in pounds is:

$$W_a = .318\,(M.T.)_a\,F_a\,a\,\frac{S}{2}\,n\,p \tag{28}$$

The mean length of turn is given by:

$$(M.T.)_a = 2\,\lambda + K^{\text{VII}}\,\tau \tag{29}$$

K^{VII} has a value of about 4.2 for 2 or 3 phase chain windings and about 3.6 for full pitch double layer windings. It is somewhat greater than 4.2 for chain windings intended for high voltage machines; and for short pitch double layer windings, it should be correspondingly reduced.

Combining (27), (28), (29) and (18),

$$W_a = \left[\frac{.159\,(2\,K^{\text{IV}} + K^{\text{VII}})\,T\,K^{\text{VI}}\,p}{I_a^2}\right](\tau\,F_a)^2 \tag{30}$$

Eliminating $a\,S$ between (1) and (27),

$$F_a\,\tau = \frac{100\,E\,I_a^2\,n}{2.22\,p \sim k\,T\,K^{\text{VI}}}\;\frac{1}{\phi} \tag{31}$$

Combining (30), (31) and (6),

$$W_a = \left\{ \frac{323 \times 10^6 \ (2\,K^{\text{IV}} + K^{\text{VII}})}{p\,T\,K^{\text{VI}}} \left[\frac{P_a}{\sim k} \right]^2 \right\} \frac{1}{\phi^2} \tag{32}$$

And

$$W_a = K^{\text{VIII}} \frac{1}{\phi^2} \tag{33}$$

where K^{VIII} is the expression in the brace in equation (32).

This equation illustrates how rapidly the cost of copper increases as the flux is reduced and we approach a "copper" machine.

If p_a represent, in dollars per pound, the price of copper used in the armature, then the cost of armature copper is:

$$S_a = p_a\,K^{\text{VIII}} \frac{1}{\phi^2} \tag{34}$$

The value of K^{VIII} should be increased by about 5 to 15 per cent. to allow for scrap.

ARMATURE ACTIVE IRON.

In punching the laminations for the armature there is always an unavoidable amount of scrap, varying from 25 to 60 per cent. This scrap, or at least a portion of it, should be charged up to the cost of the material required. It complicates the equations considerably, to bring in the iron in the teeth, while it is not very difficult to form an equation considering only the iron behind the teeth. As it is necessary to add a percentage for the scrap material, it is easy to increase this percentage so as to include the iron in the teeth. This is the method pursued, no attempt being made in the equations to find to what extent the weight of the teeth is affected by the flux.

Neglecting the fact that the diameter of the armature is not exactly the same at the bore as at the tooth roots, we have

$$W_{ai} = 0.28\,(D_1^2 - D_2^2)\,\frac{\pi}{4}\,K^{\text{IX}}\,\lambda = 0.22\,(D_1 - D_2)\,(D_1 + D_2)\,K^{\text{IX}}\,\lambda \tag{35}$$

Since we are considering only that portion of the armature active iron through which the flux passes after emerging from the teeth, the depth of the armature punching is $\frac{1}{2}(D_1 - D_2)$. If B_a represent the flux density in the armature behind the teeth, in kilolines per square inch, we have:

$$B_a = \frac{10^3 \phi}{\lambda (D_1 - D_2) K^{\text{IX}}} \tag{36}$$

Whence,

$$(D_1 - D_2) = \frac{10^3 \phi}{\lambda B_a K^{\text{IX}}} \tag{37}$$

Also

$$D_1 + D_2) = (D_1 - D_2) + 2 D_2 = \frac{10^3 \phi}{\lambda B_a K^{\text{IX}}} + 2 D_2 \tag{38}$$

But

$$D_2 = \frac{\tau p}{\pi} \tag{39}$$

Combining (18) and (39),

$$D_2 = \frac{\lambda p}{K^{\text{IV}} \pi} \tag{40}$$

Combining (35), (37), (38) and (40),

$$W_{ai} = 220 \frac{\phi}{B_a} \left(\frac{10^3 \phi}{B_a \lambda K^{\text{IX}}} + \frac{2 \lambda p}{K^{\text{IV}} \pi} \right) \tag{41}$$

Substituting for λ from equation (20),

$$W_{ai} = \left\{ \frac{22000}{B_a} \sqrt{\frac{K^{\text{II}} K B_p}{10 \sigma}} \left(\frac{1}{B_a K^{\text{IX}}} + \frac{.636 p \sigma}{K^{\text{IV}} K^{\text{II}} K B_p} \right) \right\} \phi^{\frac{3}{2}} \tag{42}$$

And

$$W_{ai} = K^{\text{X}} \phi^{\frac{3}{2}} \tag{43}$$

where K^{X} is the expression in the brace in equation (42).

The weight of armature active iron as expressed in (42), should, of course, be multiplied by a factor to allow for the weight of teeth and unavoidable scrap previously referred to. If p_{ai} represent the price, in dollars per pound, of the iron used in the armature, then the cost of armature iron S_{ai} will be:

$$S_{ai} = p_{ai} K^{\text{X}} \phi^{\frac{3}{2}} \tag{44}$$

Even in the so-called "copper machine." the cost of armature active iron is usually as great as that of the armature copper, and in most cases is slightly greater. As we depart from the "copper machine" and approach the "iron machine," the armature active iron increases very rapidly, as shown by the above equation; and this partially accounts for the fact that the "iron machine" compares unfavorably in cost with the "copper machine".

THE YOKE.

Although the mechanical design of alternator yokes has undergone many changes, the writer has been able, by comparing the weights of consistently designed yokes, to obtain an equation which will give the weight within about 15 per cent. The yokes considered for obtaining the equation belonged to a line of alternators, the bores of which were from 25 to 250 inches, and whose pole lengths were from 6 to 20 inches. They were all of modern, open type, and the material used in them was cast iron. The equation is:

$$W_y = K^{\text{XI}} D_1^{\frac{3}{2}} \lambda^{\frac{1}{2}} \tag{45}$$

W_y is the weight of the yoke in pounds, D_1 the outside diameter of the stator laminations in inches, λ the length of pole parallel to the shaft, and K^{XI} a coefficient whose value lies between 1.2 and 3, the exact value depending upon the design adopted. K^{XI} had nearly the same value for the yokes considered for obtaining the equation. The extreme values are for yokes which were very light or very heavy .

From equations (37), (39) and (18) we have

$$D_1 = D_2 + (D_1 - D_2) = \frac{\lambda\, p}{K^{\text{IV}}\, \pi} + \frac{10^3\, \phi}{\lambda\, B_a\, K^{\text{IX}}} \tag{46}$$

Hence

$$W_y = K^{\text{XI}} \lambda^{\frac{1}{2}} \left[\frac{\lambda\, p}{K^{\text{IV}}\, \pi} + \frac{10^3\, \phi}{\lambda\, B_a\, K^{\text{IX}}} \right]^{\frac{3}{2}} \tag{47}$$

In expanding the above binomial, it is unnecessary for our purposes to consider more than two terms in the series; since, except for very small diameter machines, the first term in the binomial is considerably greater than the second; and secondly, the fourth term of the series is negative and nearly cancels the positive third, the negative sixth term nearly cancels the positive fifth, etc. We have then, after expanding,

$$W_y = K^{\text{XI}}\,\lambda^{\frac{1}{2}}\left[\left(\frac{\lambda\,p}{K^{\text{IV}}\,\pi}\right)^{\frac{3}{2}} + \frac{3}{2}\left(\frac{\lambda\,p}{K^{\text{IV}}\,\pi}\right)^{\frac{1}{2}}\frac{10^3\,\phi}{B_a\,K^{\text{IX}}\,\lambda}\right] \tag{48}$$

Substituting for λ from (20) and simplifying,

$$W_y = \left\{565\,K^{\text{XI}}\sqrt{\frac{p}{K^{\text{IV}}}}\left[\frac{.318\,\sigma\,p}{K\,K^{\text{II}}\,K^{\text{IV}}\,B_p} + \frac{1.5}{K^{\text{IX}}\,B_a}\right]\right\}\phi \tag{49}$$

And $$W_y = K^{\text{XII}}\,\phi \tag{50}$$

where K^{XII} is the expression in the brace in (49).

If p_y represent the price of material used in the yoke in dollars per pound, and S_y the cost of material required for the yoke, then

$$S_y = p_y\,K^{\text{XII}}\,\phi \tag{51}$$

In order to allow for the errors introduced by neglecting the depth of the stator teeth, and by discarding all but the first two terms in the series after expanding the binominal, the value of K^{XII} should be increased by about 15 per cent.

POLES.

The radial height, H, of the pole evidently must depend upon the number of ampere turns required on full field. As previously pointed out, the full field ampere turns are proportional to the armature ampere-conductors per pole, and these latter are equal to the product of the pole pitch and ampere conductors per inch (see equation 5). Since the pole waist, W, must also be nearly proportional to the pole pitch, H should increase in some definite relation with W. Comparing the dimensions of a large number of poles for consistently designed alternators having single layer edge-wound fields, the writer has found the following relation to hold:

$$H = K^{\text{XIII}}\sqrt{W} \tag{52}$$

K^{XIII} lies between 2.5 and 4.5, depending upon the number of ampere conductors per inch; and the designer who has the data of a large number of alternators at his command, can readily determine the best value for this coefficient. H includes the radial dimension of the pole head, the projections of which are used for holding the field copper in place when the alternator is in operation; it does not include the radial dimension of the dove-tail, if dove-tails be used for fastening the poles to the field ring. If the projections of the pole head be neglected in comparison with the remainder of the pole, we may write as the weight W_P of the poles in pounds:

$$W_P = 0.28\, p\, W\, K\, \lambda\, H \tag{53}$$

Substituting for W from (12), for H from (52) and for λ from (20), we have:

$$W_P = \left\{ 1580\ p\ K^{XIII} \left(\frac{K^{II}}{K}\right)^{\frac{1}{4}} \left(\frac{\sigma}{B_P}\right)^{\frac{5}{4}} \right\} \phi^{\frac{5}{4}} \tag{54}$$

And

$$W_P = K^{XIV}\, \phi^{\frac{5}{4}} \tag{55}$$

where K^{XIV} is the expression in the brace in (54).

Representing by p_P the price, in dollars per pound, of the iron used in the poles, and by S_P the cost of material for the poles, we have:

$$S_P = p_P\, K^{XIV}\, \phi^{\frac{5}{4}} \tag{56}$$

K^{XIV} should be increased by some percentage to allow for the pole tips (which were neglected in the derivation of the equation), and for the scrap material.

FIELD RING.

In the following derivation, it is assumed that if the field ring be made sufficiently large to carry the flux (allowing for poor material, blow holes, etc.), it will be large enough for mechanical purposes. This is usually the case, although it occasionally happens that it is necessary to make the field ring heavier for mechanical reasons than would be demanded for electrical purposes.

Considering the field ring to be solid and of the same axial length as the pole, we have as its weight:

$$W_{f.r.} = .28 \times \frac{\pi}{4}\, \lambda\, (d_1^2 - d_2^2) = .22\, \lambda\, (d_1 - d_2)\, (d_1 + d_2) \tag{57}$$

But

$$(d_1 - d_2) = \frac{10^3 \phi \sigma}{B_{f.r.} \lambda} \tag{58}$$

And $$(d_1 + d_2) = 2 d_1 - (d_1 - d_2) \tag{59}$$

From (39) and (52)

$$d_1 = D_2 - 2 H = \frac{\tau p}{\pi} - 2 K^{\text{XIII}} \sqrt{W} \tag{60}$$

Combining (12), (18), (59) and (60),

$$(d_1 + d_2) = \frac{2 \lambda p}{\pi K^{\text{IV}}} - 4 K^{\text{XIII}} \sqrt{K^{\text{II}} \lambda} - \frac{10^3 \phi \sigma'}{B_{f.r.} \lambda} \tag{61}$$

Substituting (58) and (61) in (57)

$$W_{f.r.} = .22 \left(\frac{10^3 \phi \sigma'}{B_{f.r.}}\right) \left(\frac{2 \lambda p}{\pi K^{\text{IV}}} - 4 K^{\text{XIII}} \sqrt{K^{\text{II}} \lambda} - \frac{10^3 \phi \sigma'}{B_{f.r.} \lambda}\right) \tag{62}$$

Substituting for λ from (20),

$$W_{f.r.} = \left\{ \frac{4450 \sigma'}{B_{f.r.}} \sqrt{\frac{K K^{\text{II}} B_{\text{P}}}{\sigma}} \left(\frac{p \sigma}{K K^{\text{II}} K^{\text{IV}} B_{\text{P}}} - \frac{1.57 \sigma'}{B_{f.r.}} \right) \right\} \phi^{\frac{3}{2}} -$$

$$\left\{ \frac{4900 \sigma'}{B_{f.r.}} K^{\text{XIII}} \left(\frac{\sigma K^{\text{II}}}{K B_{\text{P}}} \right)^{\frac{1}{4}} \right\} \phi^{\frac{5}{4}} \tag{63}$$

And $$W_{f.r.} = K^{\text{XV}} \phi^{\frac{3}{2}} - K^{\text{XVI}} \phi^{\frac{5}{4}} \tag{64}$$

where K^{XV} and K^{XVI} are respectively the first and second expressions in braces in (63).

Representing by $p_{f.r.}$ the price in dollars per pound of the field ring material, and by $S_{f.r.}$ the cost of the field ring, we have:

$$S_{f.r.} = p_{f.r.} K^{\text{XV}} \phi^{\frac{3}{2}} - p_{f.r.} K^{\text{XVI}} \phi^{\frac{5}{4}} \tag{65}$$

K^{XV} and K^{XVI} should be increased by some percentage to allow for the spider arms, the weight of which will depend somewhat upon the flux.

COLLECTION OF TERMS FOR THE FINAL EQUATION.

Summing up the costs of material required for the principal parts of the alternator, we have

$$S_m = S_f + S_a + S_{ai} + S_y + S_P + S_{f.r.} \tag{66}$$

$$= p_f\, K^{\text{v}} \frac{1}{\phi} + p_a\, K^{\text{viii}} \frac{1}{\phi^2} + p_{ai}\, K^{\text{x}}\, \phi^{\frac{3}{2}} + p_y\, K^{\text{xii}}\, \phi + p_P\, K^{\text{xiv}}\, \phi^{\frac{5}{4}}$$

$$+ p_{f.r.}\, K^{\text{xv}}\, \phi^{\frac{3}{2}} - p_{f.r.}\, K^{\text{xvi}}\, \phi^{\frac{5}{4}} \tag{67}$$

Each of the terms in the right-hand member of equation (67) should be multiplied by some factor to allow for the unavoidable scrap and for parts which are not allowed for in the equation, such as the stator teeth, the pole tips, the spider arms, etc.

Rewriting equation (67), we have:

$$S_m = p_f\, K^{\text{v}} \frac{1}{\phi} + p_a\, K^{\text{viii}} \frac{1}{\phi^2} + (p_{ai}\, K^{\text{x}} + p_{f.r.}\, K^{\text{xv}})\, \phi^{\frac{3}{2}} + p_y K^{\text{xii}}\, \phi$$

$$+ (p_P\, K^{\text{xiv}} - p_{f.r.}\, K^{\text{xvi}})\, \phi^{\frac{5}{4}} \tag{68}$$

Or

$$S_m = \alpha_1 \frac{1}{\phi} + \alpha_2 \frac{1}{\phi^2} + \alpha_3\, \phi^{\frac{3}{2}} + \alpha_4\, \phi + \alpha_5\, \phi^{\frac{5}{4}} \tag{69}$$

where α_1, α_2, etc., are respectively p_f, K^{v}, $p_a\, K^{\text{viii}}$, etc.

Differentiating equation (69) with respect to ϕ, we have:

$$\frac{d\, S_m}{d\, \phi} = - \frac{\alpha_1}{\phi^2} - \frac{2\, \alpha_2}{\phi^3} + \frac{3}{2}\, \alpha_3\, \phi^{\frac{1}{2}} + \alpha_4 + \frac{5}{4}\, \alpha_5\, \phi^{\frac{1}{4}} \tag{70}$$

S_m will be a minimum when $\frac{d\, S_m}{d\, \phi} = 0$; hence, after clearing we have:

$$\frac{3}{2}\alpha_3\, \phi^{\frac{7}{2}} + \alpha_4\, \phi^3 + \frac{5}{4}\, \alpha_5\, \phi^{\frac{13}{4}} - \alpha_1\, \phi - 2\, \alpha_2 = 0 \tag{71}$$

This equation is of such high degree that, as well as the writer has been able to determine, it can be solved only by trial. However, after having determined the values of the various constants, the writer has been able to find that value of

ϕ which will satisfy the equation in two or three trials, requiring from three to five minutes. Equation (71) is used in determining that value of flux to employ to obtain the most economical use of material. The algebraic values of the constants occurring in equation (71) will be found in the notation.

EXAMPLE OF THE APPLICATION OF THE WRITER'S METHOD.

Design of an 800-kw. at 85% power-factor, 480 volts, three-phase, 60-cycle, 360 rev. per min. alternator to meet the following specifications:

Regulation. Rise in voltage with 800-kw. load, 100% power-factor shall not exceed 8% above normal, speed and excitation remaining constant. Rise in voltage with 800-kw. load, at 85% power-factor, shall not exceed 22% above normal, speed and excitation remaining constant.

Heating. After operating for 24 hours with 800 kw. load at 85% power-factor, the temperature rise shall not exceed 35° cent. in any part. After operating for two hours following the full-load run, with a load 25% above full load at 85% power-factor, the temperature rise shall not exceed 45° cent. in any part.

Efficiency. With 85% power-factor, the generator will have an efficiency not less than 93.5% at full load; 92.2% at 0.75 load; 89.5% at 0.50 load. Friction and windage to be included in the losses.

Excitation. The excitation will be at 120 volts. The excitation will not exceed 125 amperes when the generator yields its full load at 100% power-factor; the excitation will not exceed 180 amperes when the generator yields its full load in kilowatts at 85% power-factor.

The generator is to be capable of delivering its normal voltage of 480 when operated at 25% overload in kilowatts at 85% power-factor.

The generator must be able to stand an overspeed of 50%.

In accordance with the above specifications, the generator will have an output of 942 kilovolt-amperes, and will have 20 poles. We shall assume that if the field ring be made of cast steel, and large enough to carry the flux, it will be sufficiently strong to stand the 50% overspeed. This will be checked after the machine is designed.

As the voltage is low, the armature conductor will be large, and there will be an eddy-current loss in the copper. We shall therefore take $K^{v1} = 3.5 \times 10^4$, and $T = 30°$, allowing a margin of 5 degrees.

The alternator must have sufficient field margin to give its voltage with 25% overload in kilowatts at 85% power-factor. We shall, therefore, take $K' = 1.8$. We shall assume 23.5 kw. excitation on full field, this being 2.5% of the output of the alternator. We shall then be able to meet the excitation guarantees.

We shall assume the following values for the quantities in the equations:

$B_a = 33$; $B_{f.r.} = 63$; $B_p = 97$; $k = .96$; $K = .92$; $K' = 1.8$; $K^{\text{ii}} = .45$; $K^{\text{iii}} = .85$; $K^{\text{iv}} = 1$; $K^{\text{vi}} = 3.5 \times 10^4$; $K^{\text{vii}} = 3.7$; $K^{\text{ix}} = .81$; $K^{\text{xi}} = 1.9$; $K^{\text{xiii}} = 3.5$; $p = 20$; $p_a = .23$; $p_{ai} = .037$; $p_f = .2$; $p_{f.r.} = .036$; $p_p = .028$; $p_y = .025$; $P_a = 942$; $P_f = 23.5$; $T = 30$; $\sigma = 1.2$; $\sigma' = 1.28$; $\sim = 60$.

Substituting the above values, we obtain the following:

$K^{\text{v}} = 6300$; $K^{\text{viii}} = 23{,}000$; $K^{\text{x}} = 510$; $K^{\text{xii}} = 1180$; $K^{\text{xiv}} = 380$; $K^{\text{xv}} = 334$; $K^{\text{xvi}} = 99$.

We shall increase the value of these factors by the following percentages to allow for scrap and parts not included:

Field copper (K^{v}) 0%; armature copper (K^{viii}) 15%; armature laminations (K^{x}) 70%; poles (K^{xiv}) 25%; yoke (K^{xii}) 15%; field ring (K^{xv} and K^{xvi}) 15%.

Substituting in equation (71), we obtain

$$69\,\phi^{\frac{7}{2}} + 34\,\phi^3 + 11.5\,\phi^{\frac{13}{4}} - 1260\,\phi - 12{,}200 = 0$$

from which we find by trial that $\phi = 4.5$ megalines per pole.

We wish to build a machine that can be wound for either two or three phase, and for voltages at least as high as 2300, in order that the alternator "carcass" may be useful in the future. The first of these requirements necessitates a number of slots per pole which will be a multiple of 6. If we use 12 slots per pole, they will be rather narrow, and we must have twice as many coils as by using 6 slots, resulting in a great deal more labor. Moreover, the die work for the 12-slot punching would be considerably greater. On the other hand, for the same weight of material, the heating with the 12-slot punching would be slightly less and the wave-form slightly better. We shall, however, decide in favor of 6 slots per pole. With $\phi = 4.5$, we shall require 1.2 conductors per slot with Y connection, or 2.07 with delta connection. Using 2 conductors per slot, and connecting delta, we find that $\phi = 4.66$, which we shall adopt.

In order to find the diameter and length, we shall use equation (20) as a trial, and find $\lambda = 11.8$ inches. From (18) and (39) we find that $D_2 = 75$ in., giving a pole pitch of 11.8 inches, and a peripheral speed at the bore of 7100 ft. per minute. With this diameter we shall have 670 ampere conductors per inch.

We shall take the length of the pole λ to be 12 in. Taking the axial length of the armature to be 13.5 in., including two 0.5-in. outside, ventilating ducts, and allowing for three other 0.5-in. vents, the gross iron will be 11 in. and the net iron 9.7 in. Allowing for four teeth through which the flux will pass, and a tooth density of 98 kilolines per square inch, the tooth width will be 1.22 in. This will give a slot width of 0.75 in.

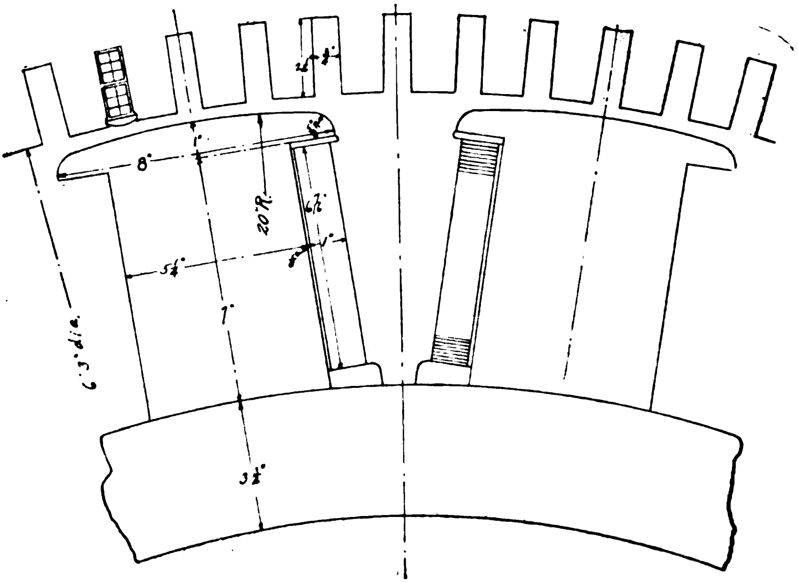

FIG. 1.

In order to reduce the eddy-current loss in the armature conductors to a minimum, we will use a double layer wave winding and laminate the conductor by using square double cotton covered wire. Two number 2 square B. & S. fit nicely in width, and allowing for three in depth in the half slot, we obtain a current density of 1670 amperes per square inch. Allowing for the stick and for insulation, we shall make the slot depth 2.25 in. Conforming with our assumed density of 33 kilolines per square inch in the armature core, we shall make the depth behind the teeth 7.25 in., corresponding to a density of 33.2.

As the pole length λ is 12 in., we find from equation (3) that W, the pole " waist ", is 5.25 in. With a 1 in. width of strip, the mean turn will be 37 in. Taking K' to be 1.8, we find from equation (5) that $X = 14{,}200$ ampere-turns. From equation (8) we find that 0.074 square inches are required. 0.07 in.x1 in. has slightly less section, but we can find from the saturation curves which will be plotted, whether this gives sufficient margin. By winding 75.5 turns on each pole, we shall meet both the temperature and excitation guarantees. This will require a radial length of pole of 7 in. excluding the head, and allowing 1 in. for the head, gives $H = 8$ in.

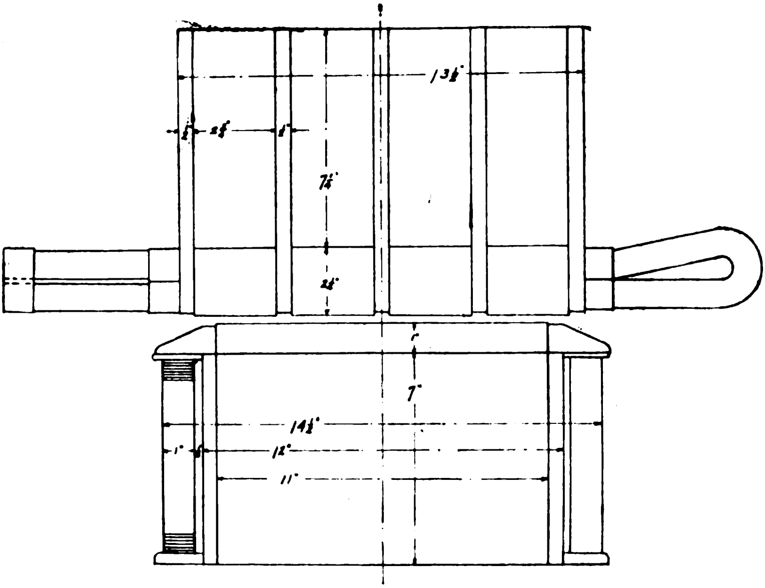

FIG. 2.

Employing cast steel for the field ring, and allowing a density of 63 kilolines per square inch, the radial depth will be 3.75 in. for an axial length of 12.5 in. Allowing 1.5 in. for the radial depth of the pole dovetail, we obtain a stress of 5200 lb. per square inch due to centrifugal force at normal speed. At 50% overspeed this will be 11,700, which is safe, as it allows a factor of safety of about 5.

In order to secure the regulation guaranteed, we shall use an air gap of 0.3 in. at the middle of the pole, making the pole eccentric with a 20 in. radius. This will make the gap ampere-turns per pole approximately 5500. The magnetic circuit of the machine is shown in Figs. 1 and 2.

The calculated saturation curves are not given, but in Fig. 3 will be found the test curves. The air-gap came a little smaller than was specified, 0.28 in. instead of 0.3 in.; but notwithstanding this discrepancy the regulation guarantees are easily met, being 7.5% and 21% with 800 kw. load and at respectively 100% and 85% power-factor. The efficiencies obtained were: full

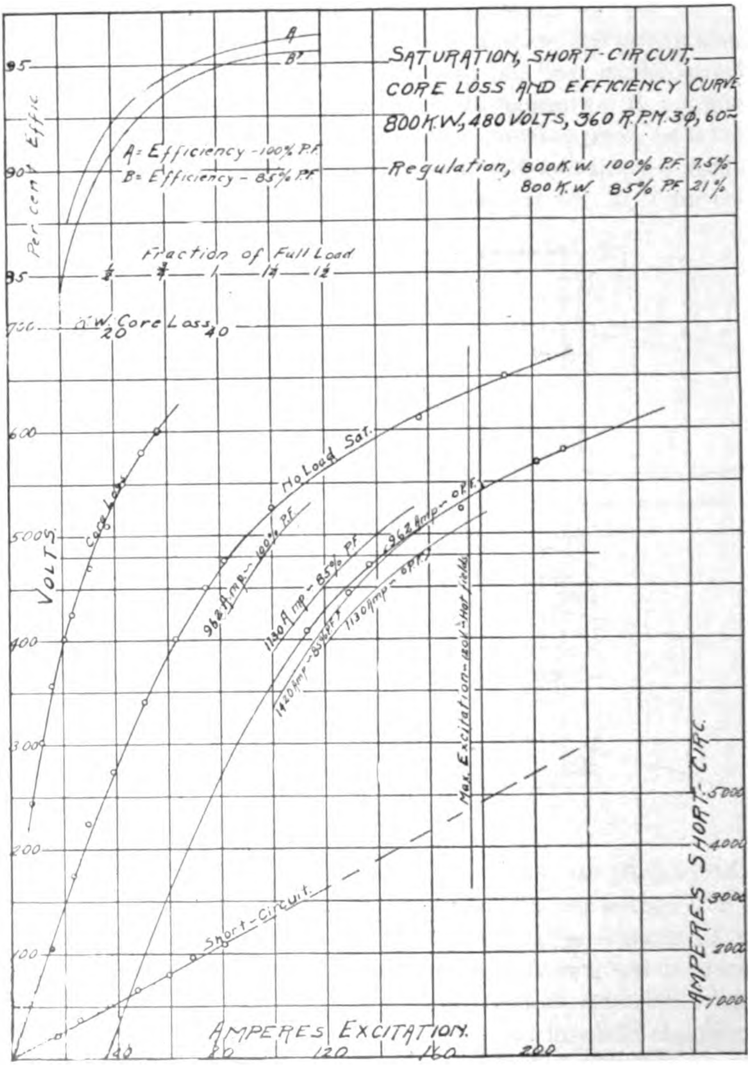

FIG. 3.

load in kilowatts, 85% power-factor, 94.72 per cent.; 0.75 load 93.54 per cent.; 0.50 load 91 per cent. The heat run showed the following results: 12 hours, 480 volts, 1005 amperes armature, 144 amperes field. Temperature rise stator iron, 22° cent.; stator coils 20° cent.; field coils 34° cent. (taken at a power-factor less than 20%). From this heat run it will be seen that the temperature rise with 800 kw. load at 85% power-factor (1130 amperes) will not exceed 25.5° cent. on the stator coils; nor will the rise exceed 40° cent. with 25% overload. As in neither case will the excitation be greater than 145 amperes, the field heating is also within the guaranteed temperature rise. It will also be seen, from an inspection of the saturation curves, that the alternator will give 535 volts when operated full field, normal speed, with 25% overload in kilowatts (1420 amperes) at 85% power-factor. The clause in the specifications calls for the alternator to give its normal voltage of 480 under these conditions.

Comparing the weights of the principal parts of the alternator as computed by means of equations (23), (33), (43), (50), (55), and (64), [employing the same value for K^{v}, K^{viii}, etc., as originally assumed ($K^{v} = 6300$, $K^{viii} = 23{,}000$, etc.), and $\phi = 4.66$], with the calculated weights determined from the dimensions of the machine, we obtain the following:

	Calculated by equation		Calculated from dimensions	
Armature copper..............	1060		1020	
Field copper..................	1360		1260	
Summation copper............		2,420		2,280
Armature laminations.........	6400*		6240	
Pole laminations..............	2860†		3350	
Yoke........................	6300‡		6300§	
Field ring....................	2700		2300	
Summation iron..............		18,260		18,190
Sum of iron and copper........		20,680		20,470

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*25% added to allow for teeth.

†10% " " " " pole tips.

‡15% " " " " inaccuracy of equation.

§Actual weight of rough casting.

In the above calculations involved in the design of the alternator, but one diameter and one length were considered. This was done in this case to prevent the paper becoming too lengthy.

The alternator as above designed well illustrates the application of the writer's method to an actual example. In an alternator for this rating it is possible to secure the same electrical characteristics by approaching either the copper or iron machine, increasing the air-gap in the former to secure regulation. Had the circulation of air been increased, thereby reducing the heating for the same weight of copper, and had the densities and other constants in the equations remained the same, the equation would have indicated a nearer approach to the copper machine. However, in a case of this kind it might be advantageous to increase the flux densities in the armature. Although the writer's method was made the basis of the design of the 800-kw. alternator given above, this was done solely for the purpose of illustrating the direct application of his method. The method is only intended to aid the designer in his work. The writer believes it to be impossible to cover the entire field of alternator design by means of a single equation.

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FUNDAMENTAL CONSIDERATIONS GOVERNING THE DESIGN OF TRANSMISSION-LINE STRUCTURES

BY D. R. SCHOLES

Before the work of designing a tower or pole for a given transmission line can proceed, a statement must be made setting forth the loads which the structure should be capable of withstanding. This statement is, in general, based on a forecast of the probable extreme weather conditions which may occur in the vicinity of the line, and also on a prediction as to what accidents will probably occur to the conductors of the line.

There is naturally considerable variation in forecasts of this sort and this variation is due primarily to a lack of accurate data regarding the various factors which enter into the case. The cost of a line is affected very largely by the figures which are selected to represent the probable extreme conditions, and the selection and application of these figures is, therefore, a matter of a good deal of importance. Unfortunately, data on this subject are very meagre, and a rational solution of a problem involving weather conditions and possible accidents is manifestly impracticable. It seems, therefore, that the best guide in selecting figures to represent the probable extreme load conditions is experience with existing transmission line structures and other structures similar to them.

During the last few years many members of the Institute have had occasion to investigate this subject, in preparing specifications for transmission lines. A discussion referring to experience with these lines and bringing out the ideas of each as to what load conditions should be provided for would be very beneficial. It is hoped that there will be such a discussion following this paper.

Figures must, in general, be selected to represent the forces which may come upon a transmission-line structure as a result of one or more of the following influences:

Wind.
Sleet.
Low temperature.
Accidents, as breaking of cables, etc.

It is also necessary to select a factor or factors of safety for use in connection with these figures, and a prediction must be made as to whether or not loads resulting from two or more of these causes are likely to occur at the same time. Considerations of cost often determine to what extent provision shall be made, in a given line, against such combinations of extreme conditions. In a very important line it may properly be considered desirable to provide strength against a combination of conditions likely to occur only once in a hundred years, whereas in a less important line the possibility of such a chance condition might, with equal propriety, be neglected.

Wind pressure on structures. The records of the weather bureau are available as an aid in estimating the maximum wind velocity to be expected in a given locality. The relation between wind velocity, however, as indicated by a government anemometer, and the actual pressure in pounds per square foot produced by a wind of that velocity on a cable or on the members of a tower, is by no means definitely known. In fact this relation is so uncertain that the most one can hope to gain from an examination of the weather reports is a general idea as to whether the winds occurring in a given locality are likely to be high or not. The anemometers of the weather bureau do not take account of sudden gusts of wind. The published velocities are not accurate, but must be corrected according to a correction table which may be obtained from the weather bureau.

The relation between wind velocity and the pressure produced by the wind on a plane surface normal to the direction of the wind is given by the formula,

$M = K V^2$, where
M = pressure in lb. per sq. ft.,
V = wind velocity in miles per hour, and
K = constant.

Experiments in general indicate that the form of this equation is correct, but experimenters differ as to the proper value of K. The values given range from 0.0035 to 0.0048. According to tests by the weather bureau, $K = 0.004$, which is probably the most reliable figure there is for K.

Experiments indicate that, in general, higher pressures are to be expected at the top of a tower than near the ground, but little is known as to how the pressure is distributed. There is considerable doubt as to what should properly be considered the exposed area of a structure; it is certain, however, that both faces are not, in general, subject to the same pressure. It is usually considered that a reduction factor of 0.5 should be used in figuring the wind pressure per square foot of projected area of cylindrical surfaces. The wide use which has been given this factor is its principal recommendation.

The purpose of the foregoing remarks on wind pressure is to point out some of the reasons for uncertainty in wind pressure calculations. In view of these uncertainties, it seems necessary to turn to some empirical method for providing against loads due to wind pressure. In bridge work pressures of from 30 to 50 lb. per square foot are commonly assumed, and these pressures are used in connection with factors of safety of from 4 to 6. Structures built to withstand loads calculated in this way are found to be strong enough. How much too strong they are is a matter of conjecture. The usual transmission line cannot stand the expense of structures built to bridge specifications. Experience with bridges cannot, therefore, be of much help in the present connection.

Steel windmill towers have been in general use for about eighteen years. Such towers are built to withstand wind loads almost exclusively and their use is very widespread. It is known that the provision against wind loads in these structures is not excessive, for there are occasional failures. The windmill tower is, in general, similar to the towers used in transmission lines. The success of a given design of windmill tower depends on what might be called the integrated experience of all the users of towers of such design. Competition has led builders to reduce their weight to a minimum. It is probable, therefore, that a windmill tower of standard design which is widely used has just about enough strength to resist the highest winds, tornadoes excepted, and it would appear that a study of such a windmill tower will probably give the best data available for use in connection with transmission line structures.

An examination of a standard design of windmill tower, of which many thousands are in use, shows that such tower will actually fail under loads calculated on the basis of wind pressures of from 40 to 50 lb. per sq. ft. The tower referred to is of square pyramidal form, and in the calculations it is assumed that the wind is blowing at right angles to one side, and both faces of the tower are considered equally exposed.

It appears, therefore, that it would be good practice in transmission line construction to specify that the poles or towers should, in addition to their other properties, have strength to resist loads on their members due to a wind pressure of 40 lb. per square foot, with a factor of safety of from 1.5 to 2, based on actual test. Such a structure would be suitable for locations where the winds are high; in other locations these figures would be reduced by judgment, aided by a consultation of the weather reports and other such data.

Factor of safety. A few remarks regarding factor of safety may be proper at this point. The factor of safety used in connection with the design of a given piece of engineering apparatus, is, in a sense, a measure of the uncertainty attending the making of calculations of the loads to be sustained or of the strength of the structure under consideration. In designing a complicated structure to sustain a complex system of loads, it would be natural and proper to allow a large factor of safety, particularly if the structure were such that it could not be tested to destruction to check all calculations and methods. On the other hand, a smaller factor of safety would be equally safe in connection with a simple structure to sustain certain definite loads, the actual ultimate strength of the structure having been determined by testing it to destruction.

The structures ordinarily used in transmission lines are simple. They are usually built in large numbers from standard designs. It is proper, therefore, that the design for such a structure should be carefully investigated and that specimen structures should be tested in such way as to remove all doubt as to their ability to withstand the loads for which they are intended. And, notwithstanding the fact that calculations of wind pressure are uncertain, experience with windmill towers removes, to a large extent, the uncertainty which would otherwise surround the figure 40 lb. per square foot which has been suggested.

Wind pressure on cables. The opinion is commonly held that, in providing against wind pressure on a surface such as that of a long span transmission line cable, it is not necessary to allow for as high a pressure as is necessary for a surface extending through smaller linear distances. Data on this subject are, as yet, very indefinite, and there is great need of specific figures for the pressure experienced on the cables of a transmission line. The following experiment is suggested as a means of securing such data.

The experimental apparatus would consist of a typical transmission line span of from 500 to 1000 ft., erected as near as possible to a weather bureau station. The cable would be fixed to the tower at one end and would pass over a pulley at its other end and be secured to a weight, this weight serving to maintain a uniform tension in the cable at all times. The position of the weight would be recorded at all times by means of a pencil and moving drum. Continuous records of temperature and wind velocity are made in the weather bureau stations. An analysis of the three records; namely, those of temperature, wind velocity, and the length of the cable in the span, would give data from which the wind pressure in pounds per square foot of projected area of the cable could be calculated. It would also be desirable to have a continuous record of the direction of wind, and this record could be readily obtained.

Records from such apparatus extending over a period of a year or more would be of much interest. It is to be observed that the readings would furnish a means of checking the coefficient of expansion of the cable. Data obtained in this way would have direct relation with the weather bureau reports, and most questions as to methods of calculation of pressure on conductors would thus be eliminated.

In the absence of specific data relating to wind pressures on the cables of long spans, it seems unsafe to assume a pressure of less than 30 lb. per sq. ft. for localities where the winds are known to be high. The figure 30 lb. per sq. ft. is commonly used in bridge calculations for surfaces extending through horizontal distances of 60 ft. or more. It seems that a factor of safety of 2 should be used in connection with this pressure, so that the conductor will not be stressed beyond its elastic limit, under extreme conditions.

Sleet. Destructive sleet storms occur in the eastern part of the United States at least as far south as Atlanta. During the past winter, a sleet storm occurred in the region of Chicago after which a coating of ice over half an inch thick was observed on conductors of various sizes. In many cases the thickness of ice at the center of the span was much greater than at the insulators, due to the tendency of the water in the sleet to run down to the lowest point while freezing. The sleet formed during this storm was practically solid ice, and it remained on the conductors for several days. In view of observations made after this storm, it is the writer's opinion that, for localities where sleet is known to form, provision should be made against a coating of ice on the cables at least one half inch thick, in combination with a factor of safety of not less than 2 based on the ultimate strength of the conductor.

There is much discussion as to whether the safety of a line demands that provision be made against sleet, low temperature, and high wind all occurring at the same time. If the sleet forms at all, it is certainly possible that it will remain on the wires several days. And if it remains on the wires several days it is certainly entirely within the range of possibility that high wind or low temperature or both will occur before it melts off. Whether or not provision should be made against a combination of these three extreme conditions becomes, therefore, entirely a question of how much the owners of the line are willing to pay for immunity from interruptions of service due to these causes. These are matters to be settled between the engineer and the owner of the line.

Accidents, as breaking of wires, etc. In providing mechanical strength in the line to resist loads due to accidents to the cables, there are two well known plans which may be followed. In the one all structures are given the same strength, each having strength to withstand the loads due to accidents which it is contemplated may occur in any span; in the other plan, two kinds of structures are used—a standard structure intended to support loads transverse to the line only, and a heavy structure having strength against the breaking strength of all the cables. These heavy structures are distributed along the line at intervals of a mile or so. The first mentioned type of construction is best adapted for lines having relatively small conductors, while the second type is favorable where the conductors are heavy.

In designing a line of the first mentioned type it is usual to assume that any two conductors may break in a given span due to the formation of an arc between them, and that the tower or pole should be capable of withstanding the loads so developed without damage to itself. Provision is not, in general, made for the simultaneous occurrence of such breakage and high wind or sleet. It would seem, however, that in such cases the towers might better be designed to withstand wind loads transverse to the line in addition to the loads due to the breakage of any two conductors, since arcing is more likely to occur in a high wind than at other times.

It is believed that the factor of safety used in connection with the loads due to breakage of conductors should be greater in the case of suspension type insulators than with pin insulators. When a conductor supported by suspension insulators breaks, it will suddenly move away from the point of breakage and will be brought to a sudden stop when the insulator comes into line with the cable. The movement will occur, in decreasing amount, all along the line, or until a strain insulator is reached. This sudden application of load and the attending inertia effect will subject the cross arm to a greater force than the tension which existed in the cable before it broke. It is suggested that cross arms be tested to loads equal to 1.25 times the elastic limit of the conductor for pin insulators and 1.5 times the elastic limit of the conductor for suspension insulators.

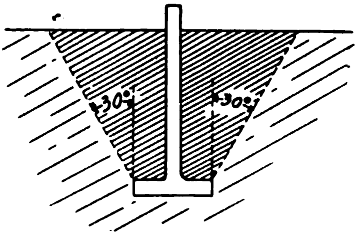

FIG. 1

Foundations. It is a usual assumption that the resistance to uplift offered by a foundation is equal to the weight of the foundation plus the weight of earth contained in the frustum indicated in Fig. 1, the angle of inclination of the sides of the frustum being 30°. The results obtained by this method agree quite closely with practice in anchors for windmill towers. In addition to resisting uplift, the foundation must, in general, have strength against horizontal forces at the ground line. The variety of designs of foundations is so great as to make a discussion of them impossible within the limits of this paper. It is suggested that, in developing the design of a foundation for a given line, tests should be made to determine the holding power, density, etc., of the soil of the locality so that the strength of the foundation will be known as accurately as the strengths of the other parts of the line.

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